Climate Dynamics
https://doi.org/10.1007/s00382-023-07084-z

# Drought projections for the NW Iberian Peninsula under climate change

**I. Alvarez[1,2] · H. Pereira[2] · M. N. Lorenzo[1] · A. Picado[2] · M. C. Sousa[2] · J. J. Taboada[3] · J. M. Dias[2]**

Received: 15 March 2023 / Accepted: 21 December 2023


**Abstract**
Drought can be considered an atmospheric condition, which rapidly goes beyond to affect multiple fields of the environment and human activities. The persistence of these atmospheric conditions can affect the recharge of surface and groundwater bodies due to a decrease in the volume of runoff and seepage, thus affecting human and environmental activities. In this context, the main aim of this work is to characterize the occurrence and variability of future droughts in Galicia over the twenty-first century. The methodology followed is based on the calculation and analysis of the Standardized Precipitation Index (SPI) in three-time scales (3, 6, and 12 months), using daily outputs of precipitation data from one RCM provided by the EURO-CORDEX project for different periods (reference from 1971 to 2005, and future from 2025 to 2060 and 2061 to 2096) and scenarios (RCP 4.5 and RCP 8.5). Using SPI-3, SPI-6, and SPI-12 projections, drought trends and potential changes in their characteristics were explored under RCP 4.5 and RCP 8.5 scenarios. In both scenarios, throughout the twenty-first century, a decreasing trend in SPI indicates an intensification of drought conditions over Galicia. Moreover, at the beginning of the century, under RCP 4.5, drought events will increase and will be slightly more intense but less persistent, while under RCP 8.5, the number of events will be almost the same, but shorter and less severe. Toward the end of the century, drought events are expected to be more numerous, less durable, and more intense under both scenarios.

**Keywords** SPI · RCP4.5 · RCP8.5 · CMIP5 · Global warming · Galicia

## 1 Introduction

Droughts may be one of the most devastating weather phenomena affecting the economy, society, and the natural environment (Lesk et al. 2016; Stanke et al. 2013; Wilhite 2000; Wilhite et al. 2007). They are rarely accurately forecasted and in most cases go unnoticed until the impacts have already occurred. To mitigate these impacts, it is necessary to know how a current drought compares with historical droughts in terms of, for example, intensity or duration. However, a comprehensive understanding of a region's drought conditions also requires an understanding of future droughts (Mishra and Singh 2010; Pokhrel et al. 2021; Spinoni et al. 2020; Stagge et al. 2015; Sun et al. 2019).

Recent trends for southern Europe, with the Mediterranean region as a hotspot, indicated a clear increase in drought frequency and intensity over the twentieth century (Briffa et al. 2009; Hoerling et al. 2012; Spinoni et al. 2015a, 2015b, 2017; Vicente-Serrano et al. 2014). In particular, the Iberian Peninsula (IP) has also presented recurrent droughts with a trend toward dryer and warmer conditions over the last decades (Ciais et al. 2005; Coll et al. 2017; García-Herrera et al. 2007; Gouveia et al. 2012; Moemken and Pinto 2022; Páscoa et al. 2017). Nevertheless, different spatial patterns were found regarding drought trends across the territory. Thus, some studies have detected a tendency for wet conditions over the northwestern region, while droughts tended to increase in the southern areas (Coll et al. 2017; Páscoa et al. 2017, 2021; Sousa et al. 2011; Vicente-Serrano et al. 2004, 2011).

✉ I. Alvarez
ialvarez@uvigo.es

[1] Centro de Investigación Mariña (CIM), Environmental Physics Laboratory (EphysLab), Universidade de Vigo, Campus da Auga, 32004 Ourense, Spain

[2] Department of Physics, CESAM-Centre for Environmental and Marine Studies, University of Aveiro, 3810-193 Aveiro, Portugal

[3] Regional Meteorological Agency (METEOGALICIA), Xunta de Galicia, Spain

Overall, there was a consensus about the northwestern region, considered an exception to the predominant trend toward drier conditions detected for most of the IP in the twentieth century. In contrast to these results, a recent work carried out in the northwestern IP from 1960 to 2020 (Lorenzo et al. 2022) indicated a general increase in drought conditions over this region toward the end of the period analyzed. Results revealed more frequent droughts during the first two decades of the twenty-first century, highlighting the need to perform separate analyses at the regional scale for the IP.

Under future climate conditions, projections for the IP indicate a change in the precipitation regime through an increase in meteorological water scarcity and frequency of drought episodes (Dai 2013; Forzieri et al. 2016; Heinrich and Gobiet 2012; Moemken et al. 2022; Ojeda et al. 2021; Spinoni et al. 2018, 2020; Stagge et al. 2015). More severe drought conditions are also projected for most of the IP. Nevertheless, different spatial distributions were observed across the territory with a north–south gradient. The worse drought conditions were identified over the southeastern region, while the northwestern region presented milder droughts. These spatial differences underline once again the importance of conducting studies at the local level to clearly identify areas where drought is projected to become more frequent and severe.

In fact, Galicia, located on the northwestern IP, constitutes an important region to study future droughts. Due to its location, Galicia is a transition area for oceanic air masses heading inland, hindering the study of climate change in the IP. This area, strongly influenced by Atlantic low-pressure systems, is the rainiest part of the IP (Rodriguez-Puebla et al. 1998; Trigo et al. 2004) and is characterized by high groundwater availability (Raposo et al. 2012, 2013). The Galician aquifers have low storage capacity and short residence time, and thus future droughts could cause a notable decrease in the availability of water resources (Feyen and Dankers 2009; Raposo et al. 2013).

In this framework, the main objective of this study is to characterize the occurrence and variability of future droughts in Galicia over the twenty-first century by the widely extensively used drought index, the SPI (Mckee et al. 1993). The projections from RCM provided by the EURO-CORDEX project with a resolution of 0.11° were used to characterize the reference period (1971–2005), and to represent the future changes in precipitation and drought for two different periods (2025–2060 and 2061–2096) and two representative concentration pathways (RCP 4.5 and RCP 8.5).

## 2 Data and methodology

### 2.1 Study area

According to the Köppen-Geiger climate classification (Kottek et al. 2006), most of the Galicia region (Fig. 1) has a warm temperate climate (Csb and Cfb according to Köppen notation).

The region is characterized by a high mean annual accumulated precipitation of around 1300 mm/year, reaching

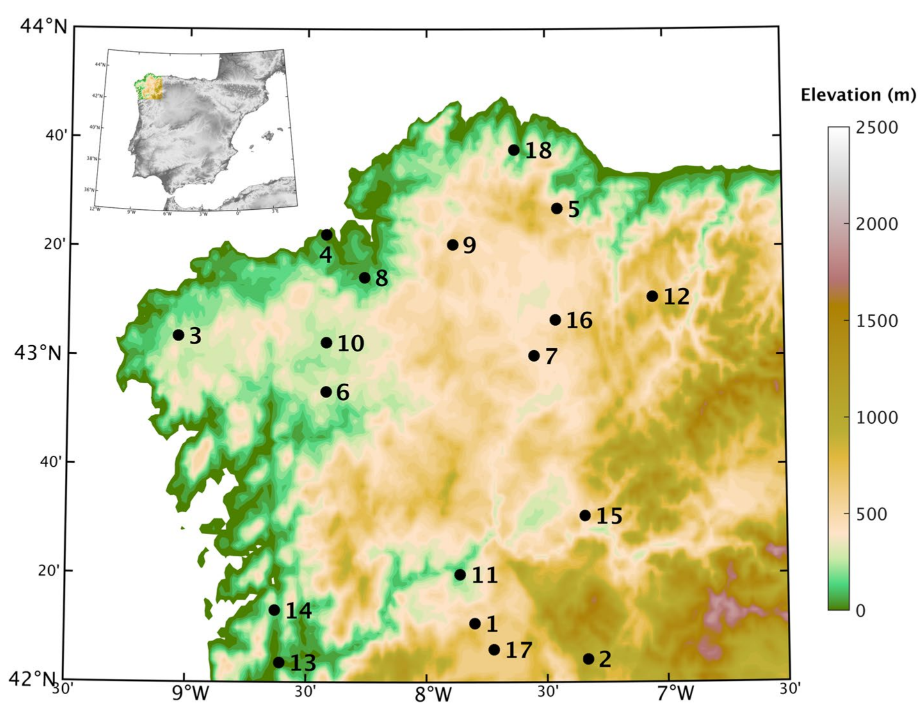


**Fig. 1** The elevation map of Galicia (meters above sea level) and the location of 18 meteorological stations (black dots)

2500 mm/year in some points of the Galician mountains, with maximum seasonal rainfall in winter and minimum in summer (Gómez-Gesteira et al. 2011). This high precipitation regime influences the existence of many small aquifers developed on fractured bedrock throughout the territory, which means high groundwater availability. These aquifers are highly dependent on rainfall recharge, and coming climatic conditions are particularly relevant in determining the amount of recharge and the availability of groundwater resources in the future (Raposo et al. 2012, 2013).

## 2.2 Model evaluation

To evaluate the numerical models' performance a comparison between observed and simulated precipitation was performed. Monthly rainfall data from 18 rain gauges (Fig. 1) were analyzed from 1971 to 2005 (reference period). These rain gauges, distributed across the study area, are managed by the Regional and National Meteorological Agencies (METEOGALICIA and AEMET), which provide data with strict quality controls. The name, code, and exact location of the rain gauges are presented in Table 1. The monthly mean precipitation for each of the 5 EURO-CORDEX models used in this study was calculated in the meteorological stations coordinates for periods concurrent with the observations. Then, the centered root mean square (RMS) difference, the standard deviation (STD), and the correlation (COR) between the time series of observations and the results of each of the models were determined, in order to assess their performance.

**Table 1** Identification, code, and coordinates of the stations represented in Fig. 1

| Name | Code | Latitude (N) | Longitude (W) |
|---|---|---|---|
| Allariz | 1 | 42.18 | 7.80 |
| Campo Becerros | 2 | 42.07 | 7.33 |
| Castrelo | 3 | 43.06 | 9.04 |
| Coruña | 4 | 43.37 | 8.42 |
| Fragavella | 5 | 43.45 | 7.45 |
| Lavacolla | 6 | 42.89 | 8.42 |
| Lugo Fingoi | 7 | 43.00 | 7.55 |
| Mabegondo | 8 | 43.24 | 8.26 |
| Marco Curra | 9 | 43.34 | 7.89 |
| Montaos | 10 | 43.04 | 8.42 |
| Ourense | 11 | 42.33 | 7.86 |
| O Xipro | 12 | 43.18 | 7.05 |
| Paramos Guillarei | 13 | 42.06 | 8.61 |
| Peinador | 14 | 42.22 | 8.63 |
| Ponte Lor | 15 | 42.51 | 7.34 |
| Rozas | 16 | 43.11 | 7.46 |
| Xinzo | 17 | 42.10 | 7.72 |
| Xunqueira | 18 | 43.63 | 7.63 |

## 2.3 Model simulations

Daily outputs of precipitation data from one RCM (Regional Climate Model—RCA4) driven by five (CNRM-CM5 (CNRM), EC-EARTH-ICHEC (ICHEC), IPSL-CM5A-MR (IPSL), HadGEM2-ES-MOHC (MOHC), and MPI-ESM-LR (MPI)) global climate models (GCMs) from the EURO-CORDEX project (http://www.euro-cordex.net/) were selected to assess future changes of drought in the study area (Fig. 1). The EURO-CORDEX initiative offers model simulations over Europe considering global climate simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) long experiments up to 2100 (Jacob et al. 2014; Taylor et al. 2012). Simulations from the RCA4 model have been selected since no other RCM from the EURO-CORDEX project has downscaled any large fraction of the CMIP5 GCMs at 0.11° resolution. In addition, precipitation simulations from this RCM have been previously used in the area under study (Lorenzo and Alvarez 2020). These projections contain two representative concentration pathways (RCPs), RCP 4.5 and RCP 8.5, based on greenhouse gas emission scenarios corresponding to the stabilization of radiative forcing after the twenty-first century at 4.5 W/m$^2$ (RCP4.5) and 8.5 W/m$^2$ (RCP8.5) (Moss et al. 2010).

## 2.4 SPI

The SPI (Mckee et al. 1993) is a widely used index to characterize droughts of different time scales. In fact, the SPI has been recommended as the world standard for determining meteorological drought by the World Meteorological Organization (WMO). This index considers rainfall as the only variable to determine whether a region during a period presents a deficit or excess of precipitation compared to normal conditions (Espinosa et al. 2019; Hayes et al. 1999; Lloyd-Hughes and Saunders 2002; Tadesse et al. 2004; Tošić and Unkašević 2014). It is a simple index that can be used seasonally, is not affected by topography, and can be calculated for different time scales (Ji and Peters 2003; Keyantash and Dracup 2002; Komuscu 1999).

The SPI does not consider other variables that may influence drought conditions as, for example, temperature. An increase in temperature implies an increase in evapotranspiration and, consequently, an unfavorable water balance, and more severe impacts upon natural systems or human activities. Nevertheless, on the one hand, the absence of quality temperature data at some of the meteorological stations considered has made it difficult to use another index. On the other hand, Galicia is characterized by a high level of rainfall over the year (Gómez-Gesteira et al. 2011), and precipitation can be considered the main driver in the temporal variability of droughts over this region (Lorenzo et al. 2022; Noguera et al. 2021). Thus, the use of the SPI is suited to identify droughts in this area.

In this work, three different time scales of 3- (SPI-3), 6- (SPI-6), and 12- (SPI-12) months were calculated and analyzed to capture both short-term and long-term droughts throughout the study area. The SPI was calculated considering rainfall data from the observation dataset and the RCM outcomes for the period 1971–2005 to evaluate the model's performance in reproducing drought characteristics. We used a gamma distribution to transform each of the historical precipitation time series. Then, the probability distribution was transformed to a standardized normal distribution to obtain the historical SPI resulting in negative values for dry conditions and positive values for wet conditions. Two future periods (2025–2060 and 2061–2096) were also analyzed to characterize drought statistics during the twenty-first century. The period 1971–2005 was used as a reference period, and future scenarios were compared to this historical period.

A drought event is identified when the SPI value is equal to or below -1.0 for at least two consecutive months. The event ends when the index recovers positive values. Then, we determine the duration and intensity of each drought event. The duration is the number of consecutive months in each drought event, and the intensity is the absolute cumulative sum of the SPI values from each event. The frequency of drought events was also analyzed as the number of events in a given period.

Also, the Mann–Kendall test (Kendall 1975; Mann 1945), a non-parametric test widely used to detect significant trends in a given dataset, was applied to identify trends in the increase and decrease of SPI. This test is frequently used in hydrological and meteorological variables and is recommended by the WMO to analyze environmental datasets (Irannezhad et al. 2016; Nashwan and Shahid 2019).

# 3 Results and discussion

## 3.1 Model evaluation

### 3.1.1 Historical precipitation

Monthly rainfall data from 1971 to 2005 measured in 18 rain gauges across Galicia (Fig. 1) were considered to validate the model's predictions. The monthly mean precipitation for each simulation from EURO-CORDEX was calculated in the coordinates of the meteorological stations (Table 1) for the same period. Figure 2 shows the centered root mean square (RMS) difference, the standard deviation (STD), and the correlation (COR) among time series used to compare observations and model results. The RMS and STD are normalized by the standard deviation of the observational database, which is considered the reference field.

All the stations show similar RMS equal to or lower than 1.5 from the five models, except stations 8 and 9. These stations, located in the northwestern region (Fig. 1), present higher RMS, especially for the IPSL model (yellow line). The same pattern can be observed for the STD, with the highest deviation also obtained for the IPSL. The most similar pattern among simulations and observations is found for the ICHEC (orange line) and MOHC (purple line) models showing lower RMS and STD. However, the STD between 1 and 1.5 achieved for the five models in most stations indicates that these models simulate the amplitude of the variations very similarly. The correlation coefficient presents low values (around 0.3) for all the simulations and stations,

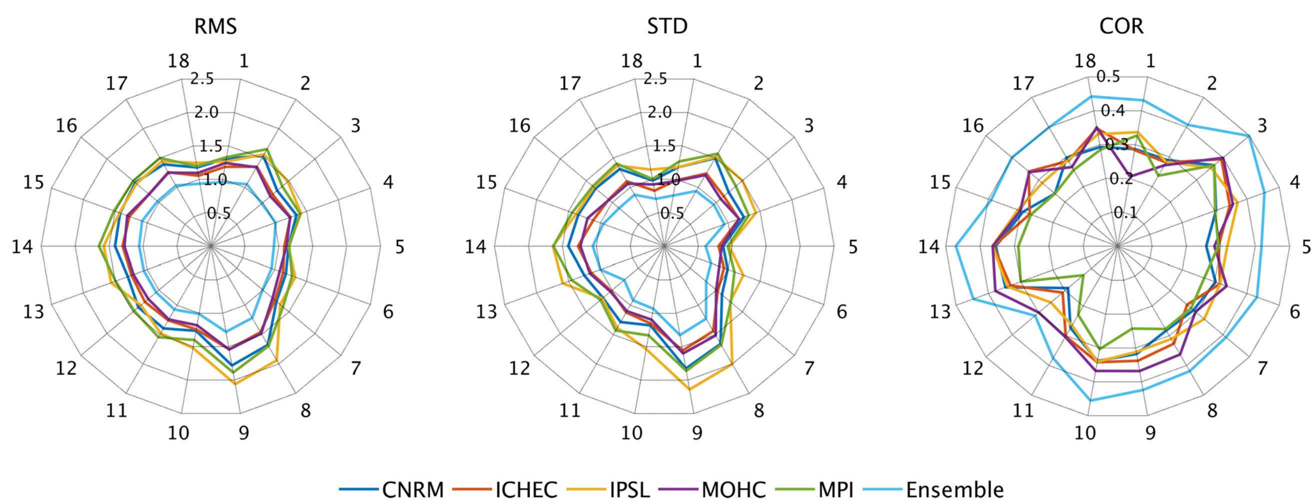


**Fig. 2** Root mean square (RMS) difference, standard deviation (STD), and correlation (COR) of the monthly precipitation measured at each meteorological station compared with simulations from 1971 to 2005

which is to be expected given the difficulty of the models in representing precipitation (Cardoso et al. 2013; Marta-Almeida et al. 2016).

Given the agreement among the different GCMs, a multimodel ensemble was considered, and the RMS, STD, and COR results are shown in Fig. 2 with a light blue line. The RMS and STD are lower for the multimodel ensemble compared to each model individually. At the same time, the correlation coefficient increases from 0.3 to over 0.4 for almost all stations indicating a better match between simulations and data.

To better examine the model's capacity to reproduce the precipitation over Galicia, the annual climatological cycle of area-averaged precipitation (mm/month) was calculated considering the multimodel ensemble and the observational dataset (Fig. 3).

Comparing the annual precipitation cycle, the average monthly precipitation obtained from the model's ensemble is consistent with observations from July to September. However, the simulated precipitation overestimates the observations from October to June, with the highest differences identified during the high precipitation months. This pattern was previously detected in different works using simulations from several RCMs over the IP during the last decades. Some authors found that the high precipitation, a characteristic of winter in Galicia, corresponds to the season and region where the models worst represent the observations (Cardoso et al. 2013; Marta-Almeida et al. 2016).

A recent work by Lorenzo and Alvarez (2020) 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), although the simulations produced higher precipitation than observed. Despite the observed differences, these works 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.

### 3.1.2 Historical droughts

The SPI was calculated at the 3-, 6- and 12-month time scales using observed and simulated precipitations from 1971 to 2005 to analyze historic drought conditions. Then, drought events were identified, and drought characteristics (number of events, duration, and intensity) were calculated. Figure 4 shows the overall statistics of drought events in the historical period for SPI-3.

In general, the number of events identified using model simulations is lower than those detected by observations. The highest difference (6 events) is obtained in stations 5 and 6, located in the northern and northwestern regions, respectively. Conversely, stations 3, 9, and 15 present the same number of observed and simulated events. Regarding drought duration, model results show slightly larger values in most stations, with the highest and lowest differences found in stations 1 and 3, respectively. The maximum observed differences are approximately three months, while some stations show minor differences (around one month). For drought intensity, most stations show slightly stronger simulated values, although, in most cases, the differences between observations and model results are minimal.

The results for the 6 and 12 months time scales are presented in Figs. 5 and 6, respectively. The number of drought events identified by observations and model simulations tends to decrease as the time scale increases. For both time scales, a good consistency can be observed for the number of detected events, showing the lowest differences between simulations and observations at the 12 months scale, where 11 of the 18 stations present differences of 1 single event. Regarding drought duration, at the 6 months time scale (Fig. 5), it is observed the same pattern as for SPI-3 (Fig. 4), with slightly longer periods for the model's simulations at all

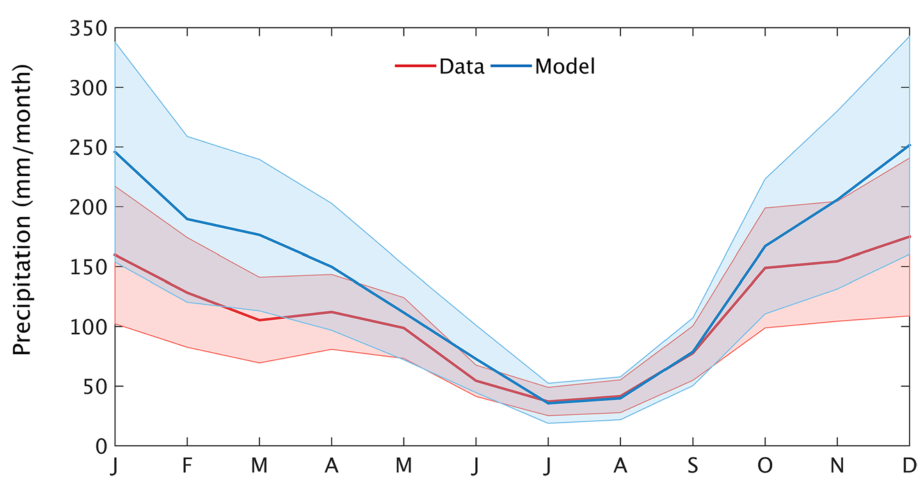


**Fig. 3** Climatological annual cycle of area-averaged precipitation (mm/month) over Galicia from 1971 to 2005 as observations (red line) and simulations (blue line). Shading denotes the data range

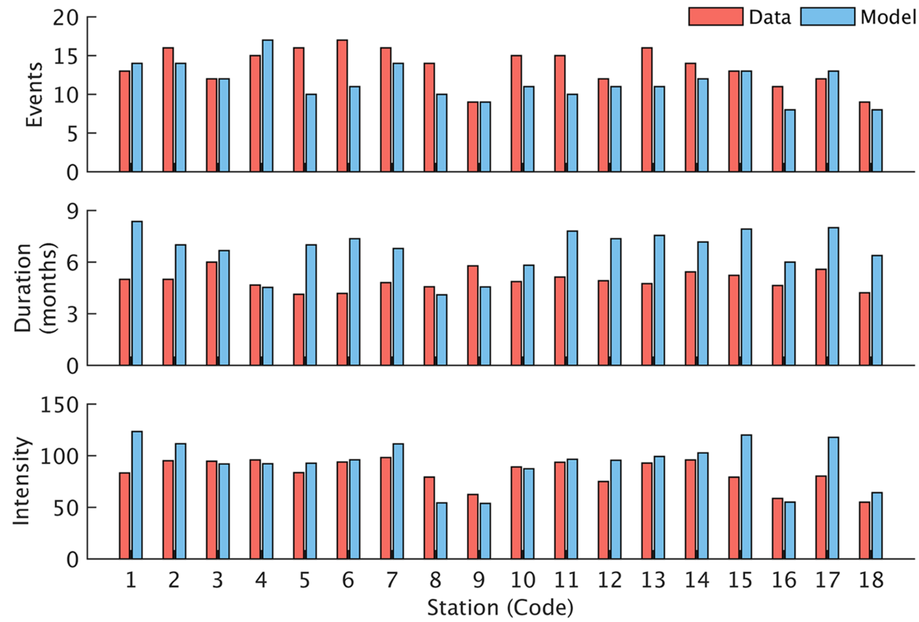


**Fig. 4** Droughts characteristics (nº of events, duration, and intensity) for the historical period considering SPI-3

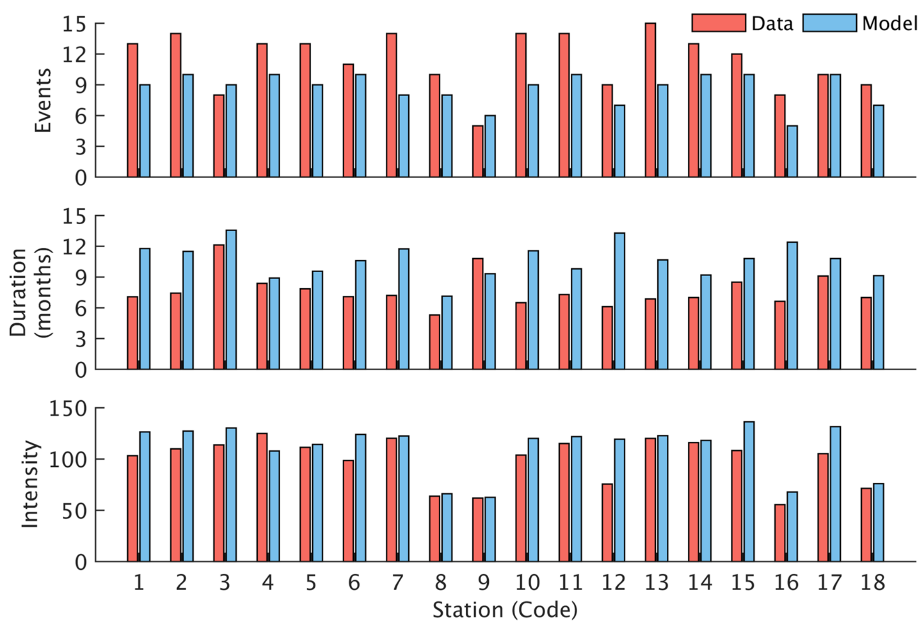


**Fig. 5** Droughts characteristics (nº of events, duration, and intensity) for the historical period considering SPI-6

stations (except station 9). Nevertheless, for SPI-12 (Fig. 6), several stations show longer observed duration. The highest differences (7 months) are obtained in stations 12 and 15 for SPI-6 and SPI-12, respectively. Even so, most stations show differences of less than 4 months. For drought intensity, SPI-6 follows the pattern of SPI-3, where a higher intensity estimated from the simulations is present at most stations. The drought intensities obtained for SPI-12 (Fig. 6) show very close values between simulations and observations, except for station 12.

From the above analysis, slight differences between the observed and simulated drought characteristics are apparent. These results indicate that despite the observed differences in the analysis of precipitation between models and observations, the models perform well in capturing drought events during the historical period, which supports the assessment of future drought in the study area with the considered models.

## 3.2 Projections for drought events

### 3.2.1 Trends

To identify possible significant trends in the future drought evolution, the increasing and decreasing trends of the SPI

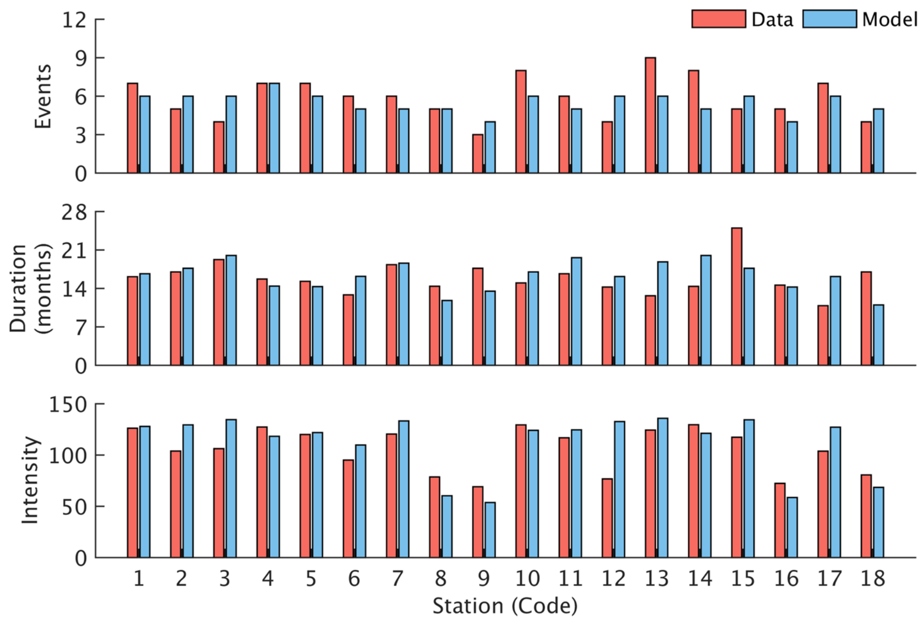


**Fig. 6** Droughts characteristics (nº of events, duration, and intensity) for the historical period considering SPI-12

were analyzed in the 18 stations (Fig. 1) considering the multimodel ensemble projections. Figure 7 shows the observed trends per decade at each station for both RCP scenarios over the period 2025–2096.

Under the RCP 4.5 scenario, a significant decreasing trend is projected across the territory at the three-time scale, indicating an intensification of drought conditions. For SPI-3 (Fig. 7a), decreasing trends between 0.03 and 0.08 per decade are expected for all stations. For SPI-6 and SPI-12 (Fig. 7b, c), the pattern is slightly different, with higher decreasing trends in the northern area (stations 5, 9, 12, and 18) reaching values close to 0.10 and 0.15 per decade for SPI-6 and SPI-12 respectively.

Concerning the RCP 8.5 scenario, similar results are found for the SPI-3 and SPI-6 (Fig. 7d, e) with decreasing trends all over the study area, being higher in the northern region, particularly at station 5 (0.10 for SPI-3, and 0.11 for SPI-6). These results are statistically significant all over the region for SPI-3, while for SPI-6 significant trends are observed mainly in the northern region. For SPI-12, Fig. 7(f) presents increasing and decreasing trends spread throughout the area. Statistically significant decreasing trends are mainly concentrated in the northern area, while most of the other stations show increasing trends. Moreover, the decreasing trends detected in the northern area are larger in magnitude than the increasing trends, around 0.10 and 0.13 per decade. The increasing trends are lower than 0.02 per decade, except at station 6 (0.04 per decade).

These results indicate a general decreasing trend in the SPI over the twenty-first century, projecting an intensification of drought conditions across the territory for both scenarios. These trends contrast with the results obtained by previous studies in the IP analyzing data for the twentieth century. Over this period, the northwest Iberian region was considered an exception to the predominant trend toward drier conditions detected over most of the region (Ojeda et al. 2021; Sousa et al. 2011; Vicente-Serrano et al. 2011; Vogel et al. 2021). In fact, humid or normal conditions have frequently been observed across Galicia throughout the last century, finding that drought events have not increased over this period. A recent work by Lorenzo et al. (2022) stated that droughts across Galicia occurred more frequently over the first two decades of the twenty-first century concerning the past century. These authors characterized drought evolution in Galicia from 1960 to 2020 using data from several rain gauges, revealing an increase in the frequency and severity of drought events toward the end of the period.

### 3.2.2 Changes in drought characteristics

Drought metrics within a 35-year reference period (1971–2005) and two future periods (2025–2060, 2061–2096) were considered to characterize future changes in drought events. Figures 8 and 9 show the projected percentual changes in the number of drought events, duration, and intensity of SPI-3 for the future RCP 4.5 and RCP 8.5 scenarios.

In the near future (Fig. 8), for RCP 4.5, model results indicate an increase in the number of events in most stations, with an increase in the event intensity at the northern stations. For RCP 8.5, the change in the number of events is more heterogeneous in all stations, ranging between − 25 and 25%, but the intensity map indicates a decrease at all stations. The duration is very similar for both scenarios, with a reduction in all stations except stations 4 and 8. For the far future (2061–2096), Fig. 9 shows that the events and

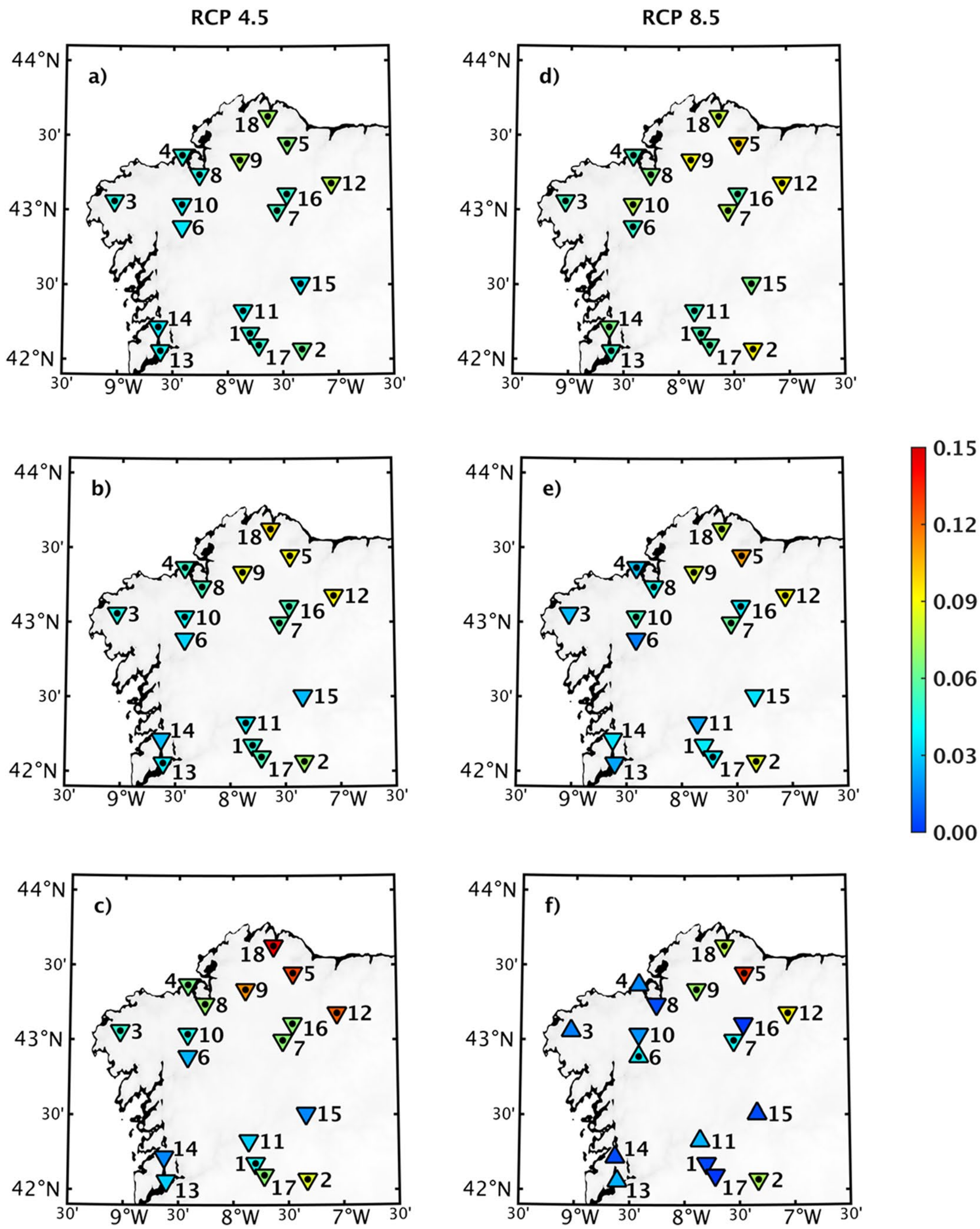


**Fig. 7** Spatial trend variation for the 18 stations according to the Man-Kendall test (tau statistic) for SPI-3 (**a**, **d**), SPI-6 (**b**, **e**), and SPI-12 (**c**, **f**) under RCP 4.5 and RCP 8.5 from 2025 to 2096. The color scale designates the magnitude of the trends. The upward (downward) triangles indicate the trend's increase (decrease). The central black point shows trends with a significance greater than 95%

intensity maps are different compared to the near future maps. The events and intensity are expected to increase for both RCP scenarios, with more severity for the RCP 8.5. The duration maps present a similar pattern to Fig. 8, but stations 4 and 8, for the RCP 4.5, in this far future, have lower durations.

For SPI-6, Figs. 10 and 11 show the events, duration, and intensity maps for the near and far futures, respectively.

The near future maps in Fig. 10 have a similar pattern to the Fig. 8 maps for both RCP scenarios. However, the percentual change in the number of events is now higher than for SPI-3. The far future maps for SPI-6 indicate an increase in the events and intensity, but a decrease in the duration. These outcomes are also similar to the SPI-3 for future maps, but in that time scale, the number of changes

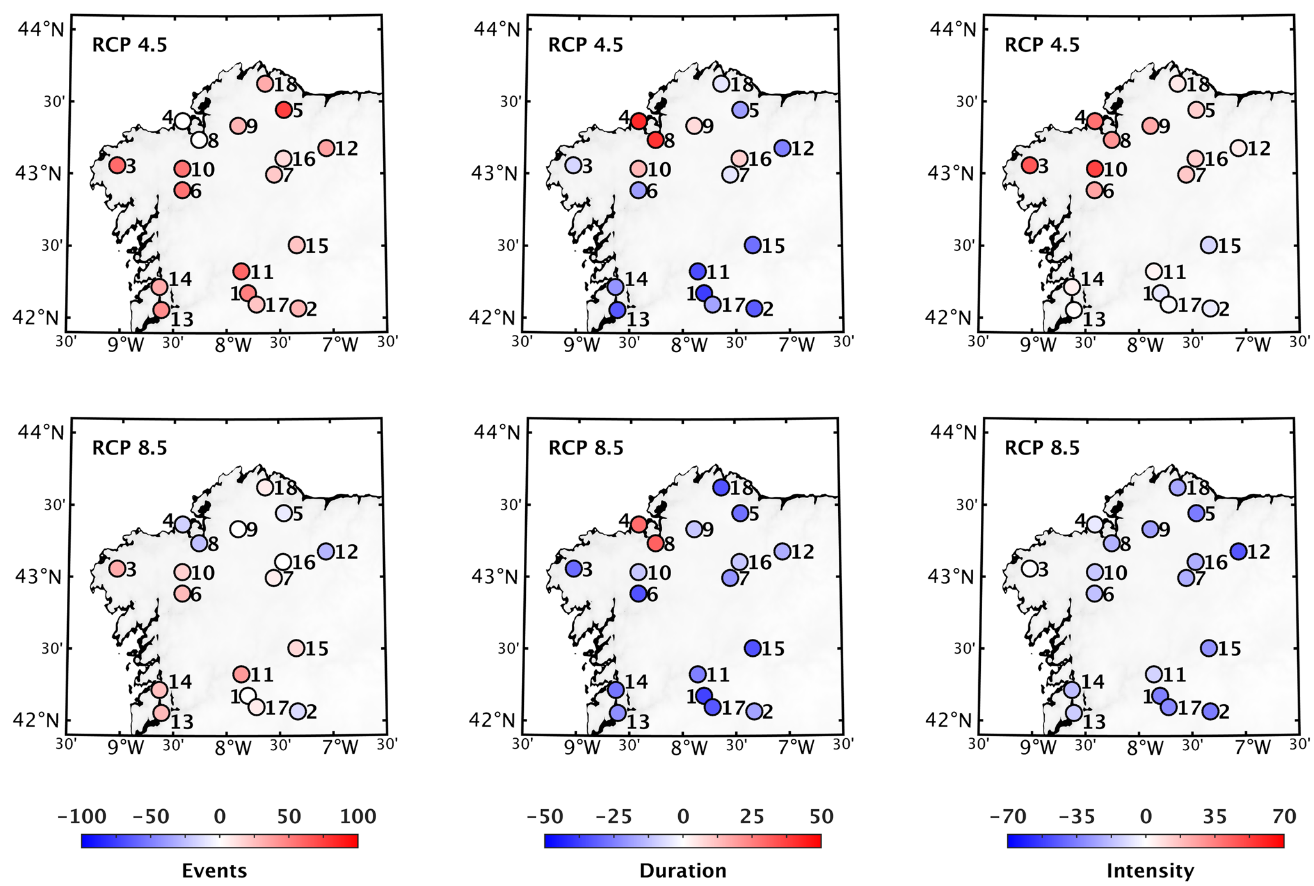


**Fig. 8** Projected changes (%) of SPI-3 metrics for drought in the period (2025–2060) under RCP4.5 and RCP8.5, relative to the reference period (1971–2005)

is higher in the events and duration maps and lower in the intensity maps.

Figures 12 and 13 present the SPI-12 results for the RCP 4.5 and 8.5 scenarios in the near and far future, respectively.

In the first, for both RCPs, the patterns are similar to the SPI-3 and SPI-6 near future maps (Figs. 8 and 10, respectively). The increase in the number of events is higher for the RCP 4.5 scenario than for RCP 8.5. The drought duration is lower for RCP 8.5, but for RCP 4.5 the changes are more heterogeneous, and the intensity maps show a slight increase for RCP 4.5 and the opposite for RCP 8.5. Regarding the far future (Fig. 13), the changes of SPI-12 show an increase in the number of events with a smaller duration in the central and south stations, but a longer duration in the northern stations. The intensity maps indicate more severity for RCP 8.5 at all stations and more moderate intensity for RCP 4.5.

Overall, these results highlight some differences between the two futures analysed and also between the two RCP scenarios. Model predictions for the RCP 4.5 indicate an increase in events at all SPIs in the near and far future. For RCP 8.5, the number of events in 2025–2060 will increase in the stations near the west coast and remain the same or diminish in eastern stations. In the far future, the number of events will increase in all stations. The future events will be shorter for both scenarios all over the century, with some exceptions at northern stations. In fact, the SPI-3 and SPI-6 project more prolonged events for the northwest stations (Figs. 8, 9, 10, and 11). Nevertheless, for SPI-12 drought events will be longer in a wider area covering the entire northern region, especially in the far future (Fig. 13). The southern stations (south station 15) will have shorter drought events for all scenarios. The near future events will be more intense for RCP 4.5, but less strong for RCP 8.5. However, in the far future, drought events are expected to be more severe for RCP 8.5. These results indicate that different patterns of drought behavior may emerge across the Galician territory in the future, highlighting that the development of regional studies is essential. However, there is still a lack of such studies over the IP, which makes comparison with our results difficult.

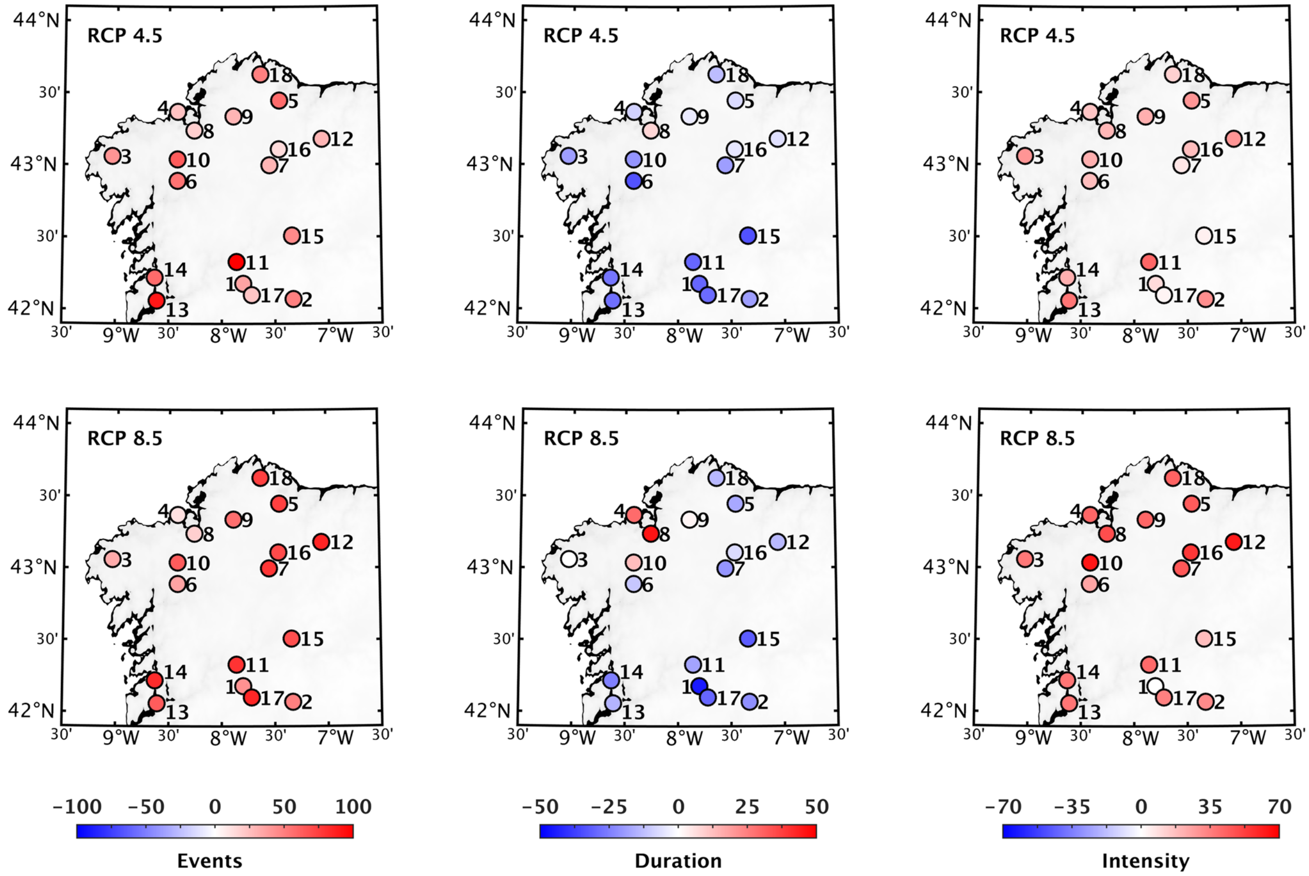


**Fig. 9** Projected changes (%) of SPI-3 metrics for drought in the period (2061–2096) under RCP4.5 and RCP8.5, relative to the reference period (1971–2005)

### 3.2.3 Discussion

Several works have been carried out in terms of future droughts throughout Europe and the IP in recent decades. Most of these studies found that western Europe, especially the IP, is projected to be characterized by an increase in the frequency and severity of droughts (Guerreiro et al. 2017; Heinrich and Gobiet 2012; Moemken et al. 2022; Naumann et al. 2018; Spinoni et al. 2018, 2020; Stagge et al. 2015). This increase is observed at the beginning of the twenty-first century and is projected to continue and grow stronger as the century passes, particularly under the RCP 8.5 scenario. Our results differ from these, as during the first half of the century, drought events are expected to be more frequent and severe for the RCP 4.5 scenario (Figs. 8, 10, and 12). Some of these studies also showed an increase in the duration of droughts for the IP, indicating that droughts will become longer-lasting. Nevertheless, our result points out that drought events will be shorter over most of the Galician territory throughout the century. This outcome could be a consequence of the shortcomings still observed in climate models.

It should be noted that our results were obtained using the SPI. The use of different indices to identify droughts could lead to potentially different results due to the variables involved in calculating the drought indices (Dubrovsky et al. 2009; Loukas et al. 2008; Touma et al. 2015). The SPI relies only on precipitation as an input variable and neglects the effect of other atmospheric variables such as temperature, and consequently of evapotranspiration.

Although many published studies around the world indicated that precipitation has a major role in explaining the occurrence of droughts, it is no novelty that the impact of enhanced evapotranspiration in a warming climate can aggravate drought conditions (Mishra and Singh 2010). Recent studies over the Iberian Peninsula have compared different drought indices which only consider precipitation and precipitation and also temperature (Gaitan et al. 2020; García-Valdecasas et al., 2021; Noguera et al. 2021; Páscoa et al. 2021; Vicente-Serrano et al. 2022; Vogel et al. 2021). The different indices detected a similar spatial occurrence of drought, although the effect of increased evapotranspiration could reinforce the severity of drought events mainly in dry areas such as the southern IP and the Mediterranean river

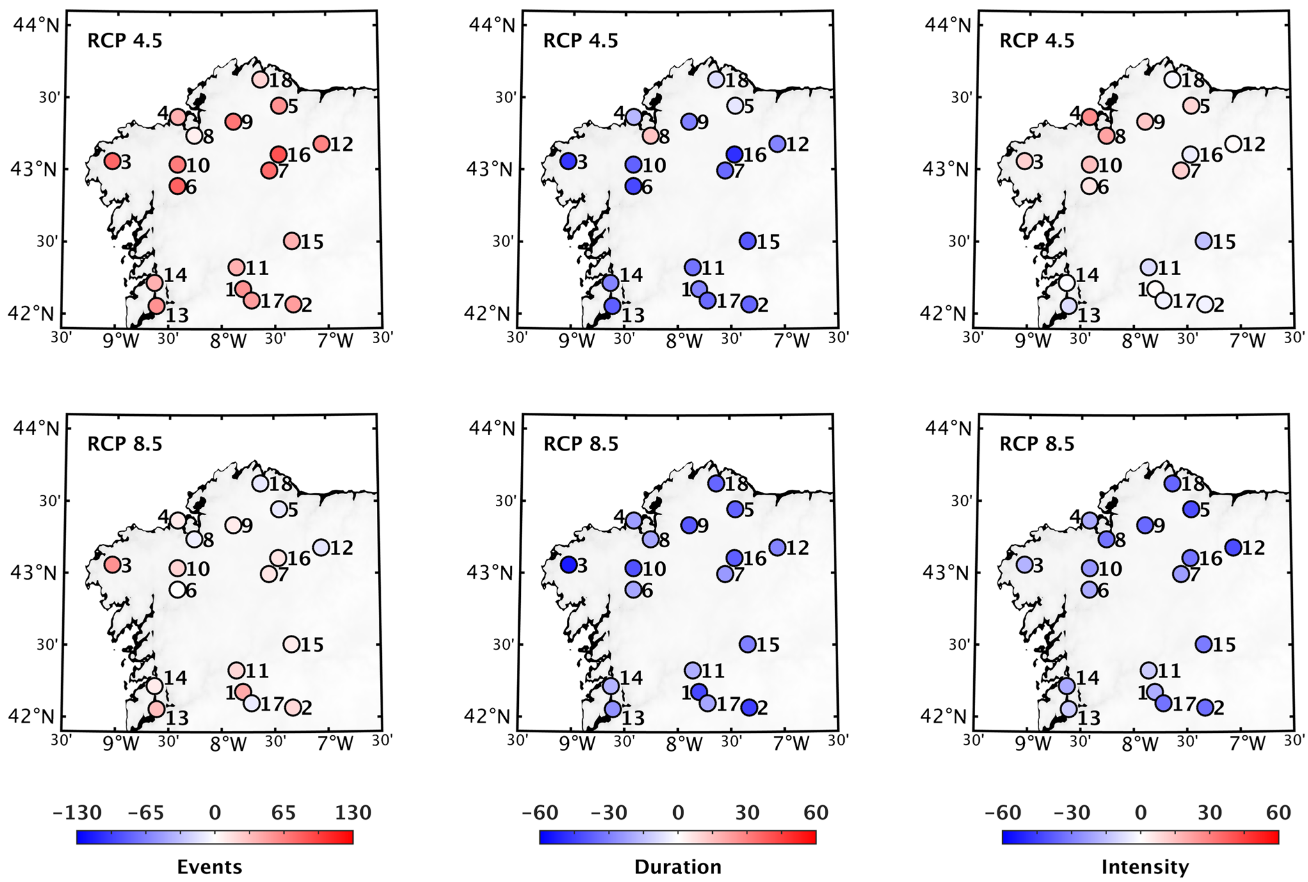


**Fig. 10** Projected changes (%) of SPI-6 metrics for drought in the period (2025–2060) under RCP4.5 and RCP8.5, relative to the reference period (1971–2005)

basins. Results corresponding to the northern areas, such as the Galician territory, are variable, although a general consensus can be derived about the precipitation deficits playing a major role in the occurrence of droughts.

Differences in the duration of future drought events among some studies and our results may also be due to the climate models considered. As shown above (Fig. 3), the analyzed models overestimate the precipitation in winter months, which is a common characteristic of several RCMs over the Galician territory (Cardoso et al. 2013; Lorenzo and Alvarez 2020; Marta-Almeida et al. 2016). These differences could directly affect the SPI calculation and drought detection. In general, there is still considerable uncertainty when it comes to the impact of climate change on precipitation in the IP due to its large spatial and temporal variability (Rodriguez-Puebla et al. 1998; Muñoz-Díaz and Rodrigo 2004; Rodrigo and Trigo 2007; Rodrigo 2010; Gallego et al. 2011; Serrano-Notivoli et al. 2018). Nevertheless, precipitation data from the EURO-CORDEX simulations have been extensively compared against observations not only by the official modelling groups but also by the scientific community. Overall, results seem consistent with the ones obtained for the observed data with an improvement in precipitation variability and extremes compared to global experiments (Fantini et al. 2018; Iles et al. 2020; Prein et al. 2016; Soares and Cardoso 2018).

Iberian precipitation also presents large interannual variability which is linked to the variability in the atmospheric circulation of mid-latitudes such as, for example, the weather types or regimes (Cortesi et al. 2013; Goodess and Jones, 2002; Rodríguez-Puebla et al. 2001; Santos et al. 2005; Zhang et al. 2015). Understanding how a warmer climate will affect atmospheric circulation over this region is essential to anticipate changes in weather conditions and could be closely related to the occurrence of extreme events such as droughts (Brunner et al. 2018; Screen and Simmonds 2014; Sousa et al. 2018; Vautard et al. 2007).

Although the present study is not oriented to analyze the synoptic causes of droughts, the latest research on the future behaviour of Atlantic atmospheric dynamics may be explored. Detecting variations in circulation is a challenging task, but some studies have analysed changes in weather regimes considering future projections over Europe and the North Atlantic region (Breton et al. 2022; Cattiaux

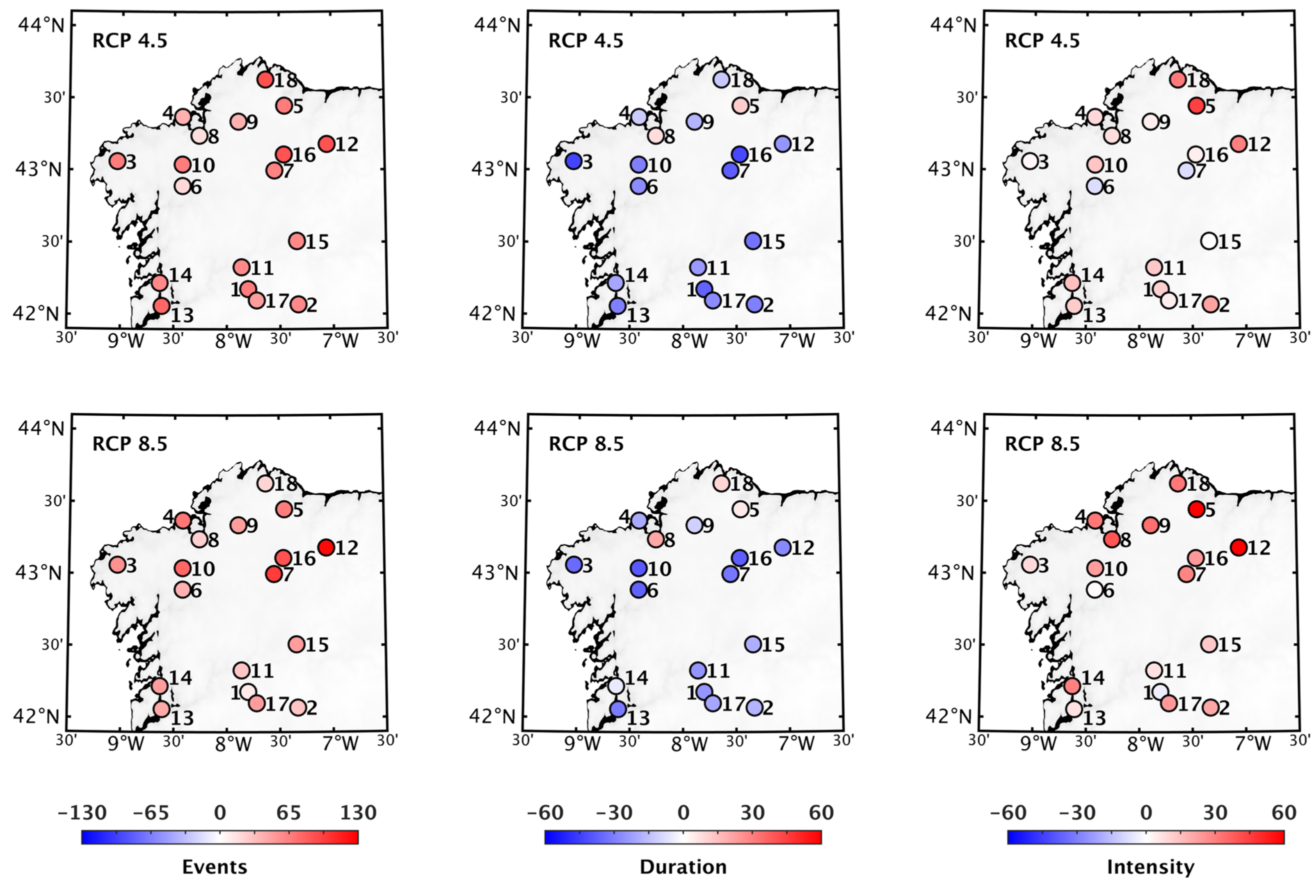


**Fig. 11** Projected changes (%) of SPI-6 metrics for drought in the period (2061–2096) under RCP4.5 and RCP8.5, relative to the reference period (1971–2005)

et al. 2013; Fabiano et al. 2021; Lorenzo et al. 2011; Ullmann et al. 2014). Some of the obtained results indicated a decrease in westerly types affecting the IP region expecting more dry conditions in the future over this area. In addition, an increase in the frequency of the positive phase of the NAO regime is also expected. This increase is associated with a north-eastward shift of the Atlantic storm track causing lower precipitation and a higher risk of droughts and heat waves over the Mediterranean region, showing an apparent consistency with our results which point out more numerous drought events toward the end of the century over the Galician territory. Even so, the link between the increase in droughts and the circulation changes must be investigated further to understand the local-scale implications of these circulation changes.

In general, our results indicate that Galicia is not an exception to the predominant trend toward drier conditions detected for the IP by previous works (Ojeda et al. 2021; Sousa et al. 2011; Vicente-Serrano et al. 2011; Vogel et al. 2021). The present study shows that, although droughts over Galicia could be less long-lasting, they will be more frequent and intense. These results agree with the observations in Galicia in the period 1960–2020 (Lorenzo et al. 2022), and are consistent with heat waves predictions, which will also be more intense and frequent (Lorenzo et al. 2021, 2022). This will lead to the need for increased attention to adaptation plans for drought-related phenomena.

The development of more regional studies in the IP is important to efficiently manage water resources, and prevent the consequences of water scarcity. Drought is an extremely regionally specific phenomenon and should possibly only be examined at the regional scale to create regional management plans that can minimize its impact (Ficklin et al. 2015). Thus, the present work could contribute to the understanding of the regional performances for drought mitigation measures and the efficient management of water resources.

## 4 Conclusions

Previous studies for the IP have identified an increase in the number of droughts, predicting that these will be more intense and frequent throughout the twenty-first century.

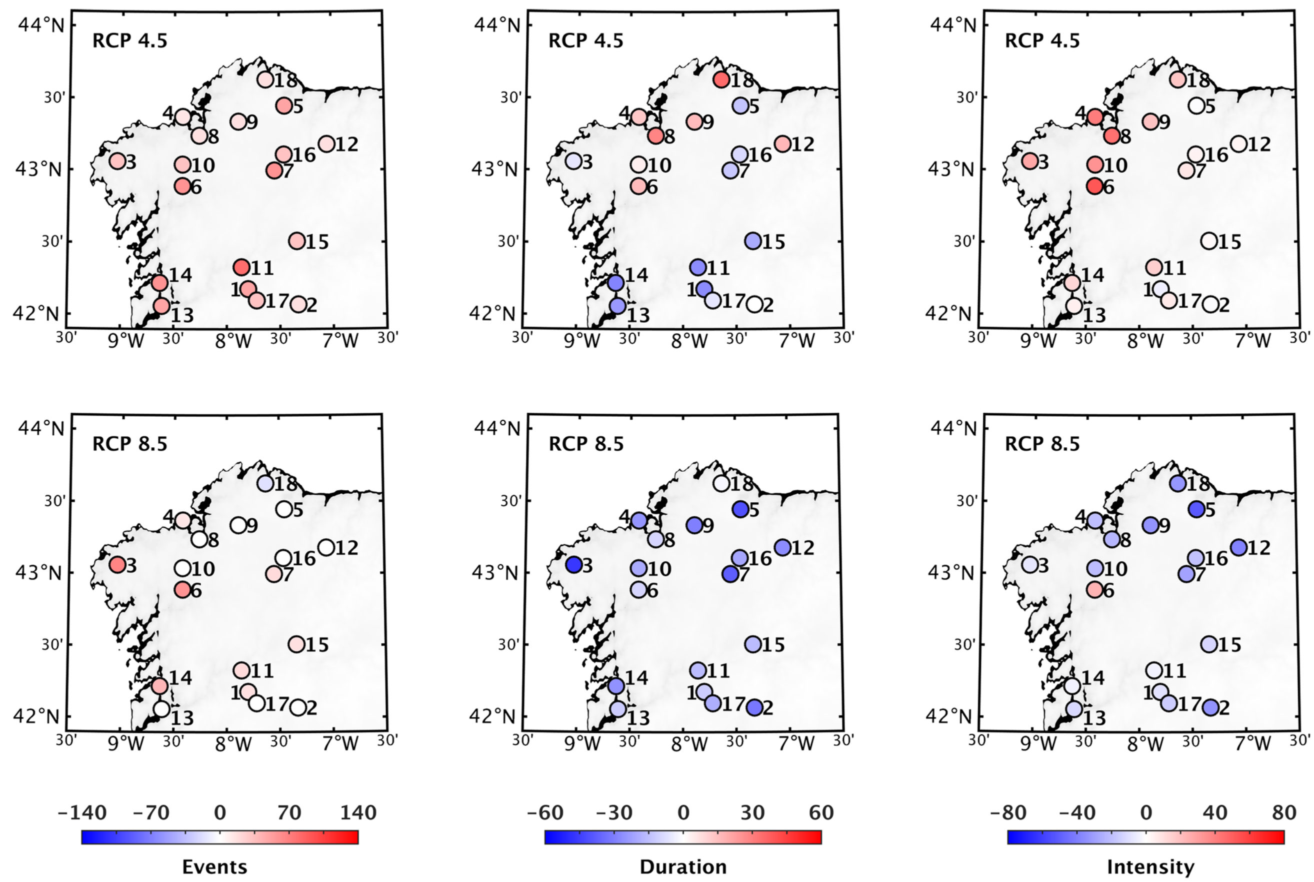


**Fig. 12** Projected changes (%) of SPI-12 metrics for drought in the period (2025–2060) under RCP4.5 and RCP8.5, relative to the reference period (1971–2005)

Yet, these variations are not uniform throughout the territory, and further analysis at a local level is necessary.

This study explored the impact of climate change in droughts over the NW region of the IP using the SPI index. This index was applied to observed rainfall data and EURO-CORDEX simulations of precipitation in three-time scales (3, 6, and 12 months) to capture short- and long-term droughts. Projections of SPI-3, SPI-6, and SPI-12 were explored under RCP 4.5 and RCP 8.5 scenarios to assess drought trends until the end of the century (2025–2096) and to assess changes in drought characteristics considering two futures (2025–2060 and 2061–2096). The main results could be summarized as follows:

- A decreasing trend in SPI over the twenty-first century projects an intensification of drought conditions over Galicia for both scenarios, with the northern region being the most affected.
- In the near future (2025–2060) of the RCP 4.5 scenario, SPI drought events will increase, being slightly more intense but less prolonged. For RCP 8.5, the number of events will be almost the same, but shorter and less severe.
- At the end of the century (2061–2096), for both scenarios, events are expected to be more numerous, less durable, and more intense. The northern region has a slightly different result for the SPI-12, where the event's duration is expected to increase.

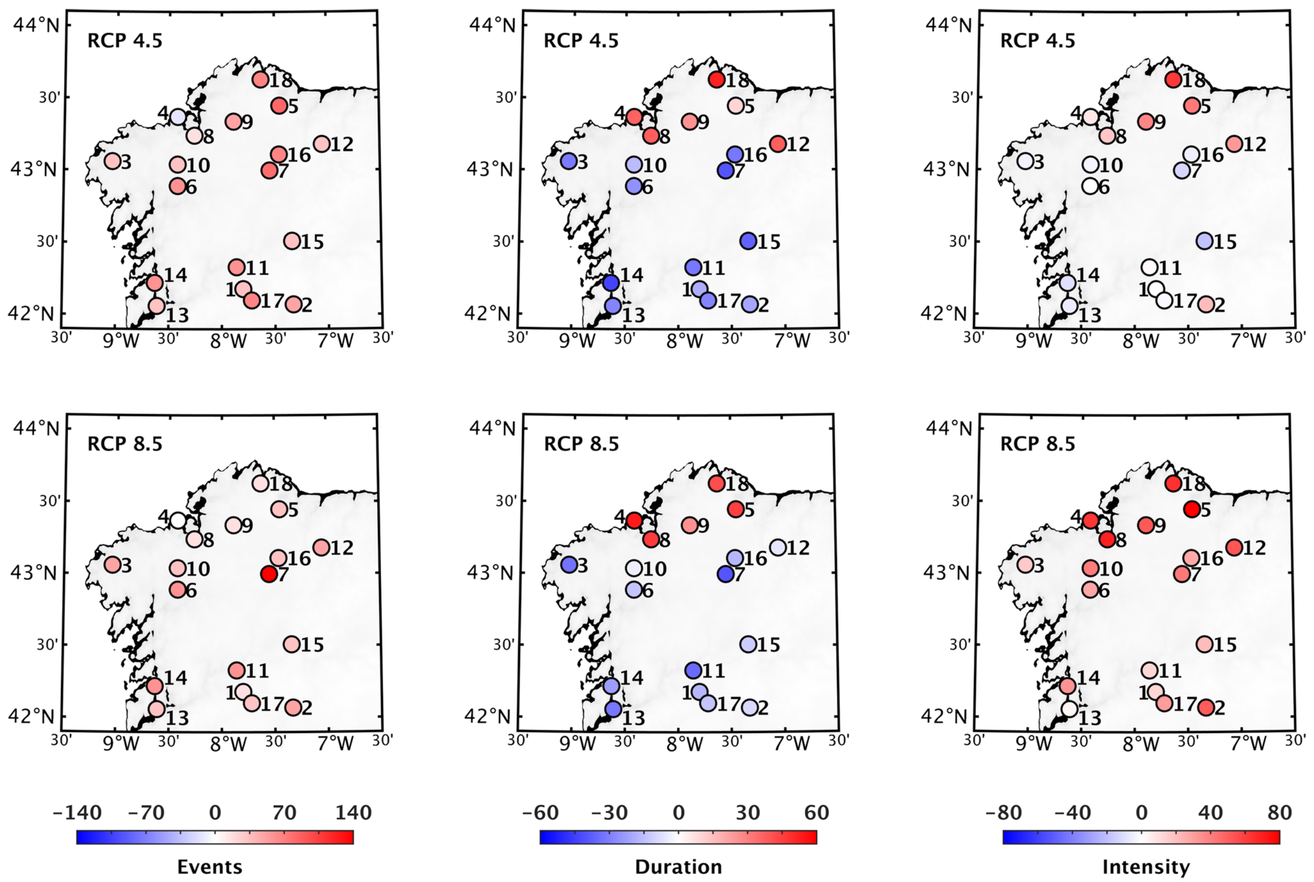


**Fig. 13** Projected changes (%) of SPI-12 metrics for drought in the period (2061–2096) under RCP4.5 and RCP8.5, relative to the reference period (1971–2005)

**Acknowledgements** This study is 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 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) and Ministerio de Ciencia e Innovacion with funding from European Union NextGenerationEU (PRTR-C17.I3) under project TED2021-129152B-C43. Humberto Pereira was funded by the Portuguese Foundation for Science and Technology (FCT), with grant number SFRH/BD/138755/2018. The authors acknowledge financial support to CESAM by FCT/MCTES (UIDP/50017/2020+UIDB/50017/2020+ LA/P/0094/2020) through national funds. Funding for open access charge: Universidade de Vigo/CISUG.

**Author contributions** All authors contributed to the study conception, design, formal analysis, investigation, methodology and writing.

**Funding** Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

**Data availability** The datasets generated during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.



## References

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(11):5848–5870. https://doi.org/10.1002/joc.7565

Briffa KR, van der Schrier G, Jones PD (2009) Wet and dry summers in Europe since 1750: evidence of increasing drought. Int J Climatol 29(13):1894–1905. https://doi.org/10.1002/joc.1836
Brunner L, Schaller N, Anstey J, Sillmann J, Steiner AK (2018) Dependence of present and future European temperature extremes on the location of atmospheric blocking. Geophys Res Lett 45:6311–6320. https://doi.org/10.1029/2018GL077837
Cardoso RM, Soares PMM, Miranda PMA, Belo-Pereira M (2013) WRF high resolution simulation of Iberian mean and extreme precipitation climate. Int J Climatol 33(11):2591–2608. https://doi.org/10.1002/joc.3616
Cattiaux J, Douville H, Peings Y (2013) European temperatures in CMIP5: origins of present-day biases and future uncertainties. Clim Dyn 41:2889–2907. https://doi.org/10.1007/s00382-013-1731-y
Ciais P, Reichstein M, Viovy N, Granier A, Ogée J, Allard V, Aubinet M, Buchmann N, Bernhofer C, Carrara A, Chevallier F, De Noblet N, Friend AD, Friedlingstein P, Grünwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Valentini R (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437(7058):529–533. https://doi.org/10.1038/nature03972
Coll JR, Aguilar E, Ashcroft L (2017) Drought variability and change across the Iberian Peninsula. Theoret Appl Climatol 130(3–4):901–916. https://doi.org/10.1007/s00704-016-1926-3
Cortesi N, Trigo RM, Gonzalez-Hidalgo JC, Ramos AM (2013) Modelling monthly precipitation with circulation weather types for a dense network of stations over Iberia. Hydrol Earth Syst Sci 17(2):665e678. https://doi.org/10.5194/hess-17-665-2013
Dai A (2013) Increasing drought under global warming in observations and models. Nat Clim Chang 3(1):52–58. https://doi.org/10.1038/nclimate1633
Dubrovsky M, Svoboda MD, Trnka M, Hayes MJ, Wilhite DA, Zalud Z, Hlavinka P (2009) Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia. Theoret Appl Climatol 96:155–171. https://doi.org/10.1007/s00704-008-0020-x
Espinosa LA, Portela MM, Rodrigues R (2019) Spatio-temporal variability of droughts over past 80 years in Madeira Island. J Hydrol 25:100623. https://doi.org/10.1016/j.ejrh.2019.100623
Fabiano F, Meccia VL, Davini P, Ghinassi P, Corti S (2021) A regime view of future atmospheric circulation changes in northern mid-latitudes. Weather Clim Dyn 2:163–180. https://doi.org/10.5194/wcd-2-163-2021
Fantini A, Raffaele F, Torma C, Bacer S, Coppola E, Giorgi F, Ahrens B, Dubois C, Sanchez E, Verdecchia M (2018) Assessment of multiple daily precipitation statistics in ERA-Interim driven Med-CORDEX and EURO-CORDEX experiments against high resolution observations. Clim Dyn 51:877–900. https://doi.org/10.1007/s00382-016-3453-4
Feyen L, Dankers R (2009) Impact of global warming on streamflow drought in Europe. J Geophys Res 114(D17):1–17. https://doi.org/10.1029/2008JD011438
Ficklin DL, Maxwell JT, Letsinger SL, Gholizadeh H (2015) A climatic deconstruction of recent drought trends in the United States. Environ Res Lett 10(4):044009. https://doi.org/10.1088/1748-9326/10/4/044009
Forzieri G, Feyen L, Russo S, Vousdoukas M, Alfieri L, Outten S, Migliavacca M, Bianchi A, Rojas R, Cid A (2016) Multi-hazard assessment in Europe under climate change. Clim Change 137(1):105–119. https://doi.org/10.1007/s10584-016-1661-x
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 MC, Trigo RM, Vaquero JM, Brunet M, García JA, Sigro J, Valente MA (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
García-Herrera R, Hernández E, Barriopedro D, Paredes D, Trigo RM, Trigo IF, Mendes MA (2007) The outstanding 2004/05 drought in the Iberian Peninsula: associated atmospheric circulation. J Hydrometeorol 8(3):483–498. https://doi.org/10.1175/JHM578.1
García-Valdecasas M, Gámiz-Fortis S, Romero-Jiménez E, Rosa-Cánovas JJ, Yeste P, Castro-Díez Y, Esteban-Parra MJ (2021) Projected changes in the Iberian Peninsula drought characteristics. Sci Total Environ 757:143702. https://doi.org/10.1016/j.scitotenv.2020.143702
Gómez-Gesteira M, Gimeno L, DeCastro M, Lorenzo M, Alvarez I, Nieto R, Taboada J, Crespo A, Ramos A, Iglesias I, Gómez-Gesteira J, Santo F, Barriopedro D, Trigo I (2011) The state of climate in NW Iberia. Climate Res 48(2):109–144. https://doi.org/10.3354/cr00967
Goodess CM, Jones PD (2002) Links between circulation and changes in the characteristics of Iberian rainfall. Int J Climatol 22(13):1593e1615. https://doi.org/10.1002/joc.810
Gouveia CM, Bastos A, Trigo RM, DaCamara CC (2012) Drought impacts on vegetation in the pre- and post-fire events over Iberian Peninsula. Nat Hazard 12(10):3123–3137. https://doi.org/10.5194/nhess-12-3123-2012
Guerreiro SB, Kilsby C, Fowler HJ (2017) Assessing the threat of future megadrought in Iberia. Int J Climatol 37(15):5024–5034. https://doi.org/10.1002/joc.5140
Hayes MJ, Svoboda MD, Wilhite DA, Vanyarkho OV (1999) Monitoring the 1996 drought using the standardized precipitation index. Bull Am Meteor Soc 80(3):429–438. https://doi.org/10.1175/1520-0477(1999)080%3c0429:MTDUTS%3e2.0.CO;2
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(13):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 of Mediterranean drought. J Clim 25(6):2146–2161. https://doi.org/10.1175/JCLI-D-11-00296.1
Iles CE, Vautard R, Strachan J, Joussaume S, Eggen BR, Hewitt CD (2020) The benefits of increasing resolution in global and regional climate simulations for European climate extremes. Geosci Model Dev 13:5583–5607. https://doi.org/10.5194/gmd-13-5583-2020
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(1):54–69. https://doi.org/10.1016/j.accre.2016.04.004
Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Déqué M, Georgievski G, Georgopoulou E, Gobiet A, Menut L, Nikulin G, Haensler A, Hempelmann N, Jones C, Keuler K, Kovats S, Yiou P (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg Environ Change 14(2):563–578. https://doi.org/10.1007/s10113-013-0499-2
Ji L, Peters AJ (2003) Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sens Environ 87(1–2):85–98. https://doi.org/10.1016/S0034-4257(03)00174-3
Kendall MG (1975) Rank correlation methods. Griffin
Keyantash J, Dracup JA (2002) The quantification of drought: an evaluation of drought indices. Bull Am Meteor Soc 83(8):1167–1180. https://doi.org/10.1175/1520-0477-83.8.1167
Komuscu AU (1999) Using the SPI to analyze spatial and temporal patterns of drought in Turkey. Drought Netw News (1994–2001) 11(1):7–13

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15(3):259–263. https://doi.org/10.1127/0941-2948/2006/0130

Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. Nature 529(7584):84–87. https://doi.org/10.1038/nature16467

Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22(13):1571–1592. https://doi.org/10.1002/joc.846

Lorenzo MN, 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 MN, Ramos AM, Taboada JJ, Gimeno L (2011) Changes in present and future circulation types frequency in Northwest Iberain Peninsula. PLoS ONE 6(1):e16201. https://doi.org/10.1371/journal.pone.0016201

Lorenzo MN, Díaz-Poso A, Royé D (2021) Heatwave intensity on the Iberian Peninsula: future climate projections. Atmos Res 258:105655. https://doi.org/10.1016/j.atmosres.2021.105655

Lorenzo MN, Alvarez I, Taboada JJ (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 HB (1945) Nonparametric tests against trend. Econometrica 13(3):245. https://doi.org/10.2307/1907187

Marta-Almeida M, Teixeira JC, Carvalho MJ, Melo-Gonçalves P, Rocha AM (2016) High resolution WRF climatic simulations for the Iberian Peninsula: model validation. Phys Chem Earth Parts a/b/c 94:94–105. https://doi.org/10.1016/j.pce.2016.03.010

Mckee T, Doesken N, Kleist J (1993) The relationship of drought frequency and duration times scales. 8th Conference on Applied Climatology, 179–184

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391(1–2):202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012

Moemken J, Pinto JG (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 JG (2022) Recurrence of drought events over Iberia. Part II: future changes using regional climate projections. Tellus A 74(2022):262–279. https://doi.org/10.16993/tellusa.52

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756. https://doi.org/10.1038/nature08823

Muñoz-Díaz D, Rodrigo F (2004) Spatio-temporal patterns of seasonal rainfall in Spain (1912–2000) using cluster and principal component analysis: comparison. Ann Geophys 22:1435–1448. https://doi.org/10.5194/angeo-22-1435-2004

Nashwan MS, Shahid S (2019) Spatial distribution of unidirectional trends in climate and weather extremes in Nile river basin. Theoret Appl Climatol 137(1–2):1181–1199. https://doi.org/10.1007/s00704-018-2664-5

Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts RA, Carrao H, Spinoni J, Vogt J, Feyen L (2018) Global changes in drought conditions under different levels of warming. Geophys Res Lett 45(7):3285–3296. https://doi.org/10.1002/2017GL076521

Noguera I, Dominguez-Castro F, Vicente-Serrano S (2021) Flash drought response to precipitation and atmospheric evaporative demand in Spain. Atmosphere 12:165. https://doi.org/10.3390/atmos12020165

Ojeda MG-V, Gámiz-Fortis SR, Romero-Jiménez E, Rosa-Cánovas JJ, Yeste P, Castro-Díez Y, Esteban-Parra MJ (2021) Projected changes in the Iberian Peninsula drought characteristics. Sci Total Environ 757:143702. https://doi.org/10.1016/j.scitotenv.2020.143702

Páscoa P, Gouveia CM, Russo A, Trigo RM (2017) Drought trends in the Iberian Peninsula over the Last 112 years. Adv Meteorol 2017:1–13. https://doi.org/10.1155/2017/4653126

Páscoa P, Russo A, Gouveia CM, Soares PMM, Cardoso RM, Careto JAM, Ribeiro AFS (2021) A high-resolution view of the recent drought trends over the Iberian Peninsula. Weather Clim Extremes 32:100320. https://doi.org/10.1016/j.wace.2021.100320

Pokhrel Y, Felfelani F, Satoh Y, Boulange J, Burek P, Gädeke A, Gerten D, Gosling SN, Grillakis M, Gudmundsson L, Hanasaki N, Kim H, Koutroulis A, Liu J, Papadimitriou L, Schewe J, Müller Schmied H, Stacke T, Telteu C-E, Wada Y (2021) Global terrestrial water storage and drought severity under climate change. Nat Clim Change 11(3):226–233. https://doi.org/10.1038/s41558-020-00972-w

Prein AF, Gobiet A, Truhetz H, Keuler K, Goergen K, Teichmann C, Fox Maule C, van Meijgaard E, Deque M, Nikulin G, Vautard R, Colette A, Kjellstrom E, Jacob D (2016) Precipitation in the EURO-CORDEX 0.11∘ and 0.44∘ simulations: high resolution, high benefits? Clim Dyn 46:383–412. https://doi.org/10.1007/s00382-015-2589-y

Raposo JR, Molinero J, Dafonte J (2012) Parameterization and quantification of recharge in crystalline fractured bedrocks in Galicia-Costa (NW Spain). Hydrol Earth Syst Sci 16(6):1667–1683. https://doi.org/10.5194/hess-16-1667-2012

Raposo JR, Dafonte J, Molinero J (2013) Assessing the impact of future climate change on groundwater recharge in Galicia-Costa, Spain. Hydrogeol J 21(2):459–479. https://doi.org/10.1007/s10040-012-0922-7

Rodrigo FS (2010) Changes in the probability of extreme daily precipitation observed from 1951 to 2002 in the Iberian Peninsula. Int J Climatol 30:1512–1525. https://doi.org/10.1002/joc.1987

Rodrigo FS, Trigo RM (2007) Trends in daily rainfall in the Iberian Peninsula from 1951 to 2002. Int J Climatol 27:513–529. https://doi.org/10.1002/joc.1409

Rodriguez-Puebla C, Encinas AH, Nieto S, Garmendia J (1998) Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula. Int J Climatol 18(3):299–316. https://doi.org/10.1002/(SICI)1097-0088(19980315)18:3%3c299::AID-JOC247%3e3.0.CO;2-L

Rodríguez-Puebla C, Encinas AH, Saenz J (2001) Winter precipitation over the Iberian Peninsula and its relationship to circulation indices. Hydrol Earth Syst Sci 5(2):233e244. https://doi.org/10.5194/hess-5-233-2001

Santos JA, Corte-Real J, Leite SM (2005) Weather regimes and their connection to the winter rainfall in Portugal. Int J Climatol 25(1):33e50. https://doi.org/10.1002/joc.1101

Screen JA, Simmonds I (2014) Amplified mid-latitude planetary waves favour particular regional weather extremes. Nat Clim Chang 4:704–709. https://doi.org/10.1038/nclimate2271

Serrano-Notivoli R, Beguería S, Saz MA, de Luis M (2018) Recent trends reveal decreasing intensity of daily precipitation in Spain. Int J Climatol 38:4211–4224. https://doi.org/10.1002/joc.5562

Soares PMM, Cardoso RM (2018) A simple method to assess the added value using high-resolution climate distributions: application to the EURO-CORDEX daily precipitation. Int J Climatol 38:1484–1498. https://doi.org/10.1002/joc.5261

Sousa PM, Trigo RM, Aizpurua P, Nieto R, Gimeno L, Garcia-Herrera R (2011) Trends and extremes of drought indices throughout the

20th century in the Mediterranean. Nat Hazard 11(1):33–51. https://doi.org/10.5194/nhess-11-33-2011
Sousa PM, Trigo RM, Barriopedro D, Soares PM, Santos JA (2018) European temperature responses to blocking and ridge regional patterns. Clim Dyn 50(457–477):2018. https://doi.org/10.1007/s00382-017-3620-2
Spinoni J, Naumann G, Vogt J, Barbosa P (2015a) European drought climatologies and trends based on a multi-indicator approach. Global Planet Change 127:50–57. https://doi.org/10.1016/j.gloplacha.2015.01.012
Spinoni J, Naumann G, Vogt JV, Barbosa P (2015b) The biggest drought events in Europe from 1950 to 2012. J Hydrol 3:509–524. https://doi.org/10.1016/j.ejrh.2015.01.001
Spinoni J, Naumann G, Vogt JV (2017) Pan-European seasonal trends and recent changes of drought frequency and severity. Global Planet Change 148:113–130. https://doi.org/10.1016/j.gloplacha.2016.11.013
Spinoni J, Vogt JV, Naumann G, Barbosa P, Dosio A (2018) Will drought events become more frequent and severe in Europe? Int J Climatol 38(4):1718–1736. https://doi.org/10.1002/joc.5291
Spinoni J, Barbosa P, Bucchignani E, Cassano J, Cavazos T, Christensen JH, Christensen OB, Coppola E, Evans J, Geyer B, Giorgi F, Hadjinicolaou P, Jacob D, Katzfey J, Koenigk T, Laprise R, Lennard CJ, Kurnaz ML, Li D, Dosio A (2020) Future global meteorological drought hot spots: a study based on CORDEX data. J Clim 33(9):3635–3661. https://doi.org/10.1175/JCLI-D-19-0084.1
Stagge J, Tallaksen L, Rizzi J (2015) Future meteorological drought: projections of regional climate models for Europe. EGU General Assembly Conference Abstracts
Stanke C, Kerac M, Prudhomme C, Medlock J, Murray V (2013) Health effects of drought: a systematic review of the evidence. PLoS Currents. https://doi.org/10.1371/currents.dis.7a2cee9e980f91ad7697b570bcc4b004
Sun CX, Huang GH, Fan Y, Zhou X, Lu C, Wang XQ (2019) Drought occurring with hot extremes: changes under future climate change on Loess Plateau, China. Earth's Future 7(6):587–604. https://doi.org/10.1029/2018EF001103
Tadesse T, Wilhite DA, Harms SK, Hayes MJ, Goddard S (2004) Drought monitoring using data mining techniques: a case study for Nebraska, USA. Nat Hazards 33(1):137–159. https://doi.org/10.1023/B:NHAZ.0000035020.76733.0b
Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteor Soc 93(4):485–498. https://doi.org/10.1175/BAMS-D-11-00094.1
Tošić I, Unkašević M (2014) Analysis of wet and dry periods in Serbia. Int J Climatol 34(5):1357–1368. https://doi.org/10.1002/joc.3757
Touma D, Ashfaq M, Nayak MA, Kao SC, Diffenbaugh NS (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
Trigo RM, Pozo-Vázquez D, Osborn TJ, Castro-Díez Y, Gámiz-Fortis S, Esteban-Parra MJ (2004) North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. Int J Climatol 24(8):925–944. https://doi.org/10.1002/joc.1048
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
Vautard R, Yiou P, D'Andrea F, de Noblet N, Viovy N, Cassou C, Polcher J, Ciais P, Kageyama M, Fan Y (2007) Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. Geophys Res Lett 34:L07711. https://doi.org/10.1029/2006GL028001
Vicente-Serrano S, González-Hidalgo J, de Luis M, Raventós J (2004) Drought patterns in the Mediterranean area: the Valencia region (eastern Spain). Climate Res 26:5–15. https://doi.org/10.3354/cr026005
Vicente-Serrano S, López-Moreno J, Drumond A, Gimeno L, Nieto R, Morán-Tejeda E, Lorenzo-Lacruz J, Beguería S, Zabalza J (2011) Effects of warming processes on droughts and water resources in the NW IberianPeninsula (1930–2006). Climate Res 48(2):203–212. https://doi.org/10.3354/cr01002
Vicente-Serrano SM, Lopez-Moreno J-I, Beguería S, Lorenzo-Lacruz J, Sanchez-Lorenzo A, García-Ruiz JM, Azorin-Molina C, Morán-Tejeda E, Revuelto J, Trigo R, Coelho F, Espejo F (2014) Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ Res Lett 9(4):044001. https://doi.org/10.1088/1748-9326/9/4/044001
Vicente-Serrano SM, Dominguez-Castro F, Reig F, Beguería JI, Tomas-Burguera M, Latorre B, Peña-Angulo D, Noguera I, Rabanaque I, Luna Y, Morta A, ElKenawy 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 Extremes 32:100312. https://doi.org/10.1016/j.wace.2021.100312
Wilhite DA (2000) Drought as a natural hazard: concepts and definitions. Drought: a global assessment, Donald, pp 3–18
Wilhite DA, Svoboda MD, Hayes MJ (2007) Understanding the complex impacts of drought: a key to enhancing drought mitigation and preparedness. Water Resour Manag 21(5):763–774. https://doi.org/10.1007/s11269-006-9076-5
Zhang W, Wang L, Xiang B, Qi L, He J (2015) Impacts of two types of La Niña on the NAO during boreal winter. Clim Dyn. https://doi.org/10.1007/s00382-014-2155-z

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.