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Recurrence of Drought Events Over Iberia. Part I: Methodology and Application for Present Climate Conditions

ORIGINAL RESEARCH PAPER

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ABSTRACT

Seasonal drought is a typical feature of the Mediterranean climate that may lead to strong socioeconomic and ecological impacts. We investigate the occurrence and intensity of historical extreme drought events over the Iberian Peninsula (IP) for the past decades, with special focus on recurrent drought events. With this aim, we introduce and apply a new set of indices: The Recurrent Dry Year Index (RDYI) and the Consecutive Drought Year (CDY) Index. Additionally, three drought indices are considered for individual events: A simple Drought Index (DI) based on precipitation deficits and the number of affected grid points, the Effective Drought Index (EDI), and the Standardized Precipitation Index (SPI). Different gridded observational (E-OBS V20e, IBERIA01) and reanalysis datasets (ERA5) are analysed at several spatial resolutions, ranging roughly between 10km and 25km.

Results show that extreme droughts are a common feature in the IP, with roughly three individual events per decade. Especially the southern and central parts of IP are exposed to recurrent events. These events typically last two to three years, but may reach a length of six consecutive years. Sensitivity in the number of drought years is found regarding the spatial resolution. Moreover, drought is identified more often with EDI, leading to an enhanced number of recurrent droughts. (Recurrent) Droughts in IP are driven by precipitation deficits in winter (rainiest season) as there is hardly any precipitation during summer over most of IP. Still, deficits in spring and autumn may also be decisive, and some sensitivity is identified regarding the choice of index and the affected region. We conclude that the new indices are suitable for the detection and analysis of recurrent drought events. They are a first step towards a systematic worldwide evaluation of recurrent drought events under present and future climate conditions.

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1. INTRODUCTION

Weather and climate extreme events lead to severe impacts worldwide (World Economic Forum, 2019), and the development of better physical understanding, quantitative forecasts and early warning systems is of crucial importance (Merz et al., 2020). Drought events are one of the most impacting natural disasters worldwide (Spinoni et al., 2018), and can have severe impacts on various natural and human systems, including hydrology, agriculture, economy, society or environment. These impacts are specific to the field of interest and to the region of occurrence (Zink et al., 2016). Droughts are characterized by a deficit in precipitation over a certain period of time (WMO, 2006; Mishra and Singh, 2010). Thus, precipitation is the main variable controlling the onset, duration, end, intensity and variability of droughts (Chang and Kleopa, 1991; Heim, 2002; Vicente-Serrano et al., 2020). However, droughts are caused by a complex interaction of atmospheric, hydrological and biophysical processes (Touma et al., 2015). This complexity is expressed by a wide variety of definitions as well as a large collection of indicators used to identify and analyse the individual drought types: meteorological, agricultural, hydrological, and socioeconomic (Heim, 2002; WMO, 2006; Mishra and Singh, 2010).

Drought events are a frequent feature of the European climate. During 2006 to 2010, around 15% of the EU territory and 17% of the EU population have experienced a meteorological drought event each year (EEA, 2016). One hot spot in Europe is the Mediterranean region, which is characterised by a pronounced seasonality of precipitation, with very low values in the summer months. Here, the frequency of drought has been particularly high in the last decades (e.g. Spinoni et al., 2015a; b): 10 out of the 12 driest winters since 1902 occurred between 1970 and 2010, indicating an increased trend (Hoerling et al., 2012). In the Iberian Peninsula (IP), droughts are a common phenomenon with mounting impacts (García-Herrera et al., 2007; Gouveia et al., 2009; Trigo et al., 2013; Coll et al., 2017). The Iberian precipitation regime is characterized by a strong inter-annual and decadal variability as well as a large spatial heterogeneity (Esteban-Parra et al., 1998). The largest precipitation amount is typically recorded in the winter half year between October and March (Esteban-Parra et al., 1998; Trigo and DaCamara, 2000; Trigo et al., 2004; Paredes et al., 2006), while the summer precipitation has limited to no impact on the total annual precipitation amount (seasonal summer drought). Accordingly, all major drought events in the IP occurred due to precipitation deficits in the winter half year (Trigo and DaCamara, 2000). Several studies agree on an increase in drought severity and intensity in recent decades (e.g. EEA, 2016; Coll et al., 2017, Páscoa et al., 2017; Spinoni et al., 2017), mostly associated with drying trends. However, trends are often not significant (Vicente-Serrano et al., 2020). Under future climate conditions, projections suggest an increase in the frequency, intensity and duration of extreme droughts for large parts of the IP for the 21st century, a signal common to many other regions worldwide (Seneviratne et al., 2012; Kirtman et al., 2013; Stagge et al., 2015; Spinoni et al., 2018; 2020).

So far, most studies focus on the incidence, physical characteristics and impacts of individual drought events. However, with an enhanced year-to-year variability and a long-term drying trend, the probability of multiple events in a decade and hence the likelihood of droughts recurring in consecutive years becomes higher. The occurrence of such temporal compounding events (Zscheischler et al., 2020) aggravates the impacts. Recurrent drought events, for instance, may lead to intensified negative impacts and a critical destabilization and/or increasing competition of the different water using sectors. For example, the occurrence of consecutive severe droughts alters ecosystem processes (e.g. hydrological cycle, plant productivity; Caldeira et al., 2015), and can thus critically affect the balance of the ecosystem itself (Ciais et al., 2005).

For the first time, our study focuses on the recurrence of dry/drought events in consecutive years for IP and presents a new set of indices for their identification and analysis. We compare several definitions for such recurrent events, ranging from precipitation deficits (relative to climatology) to classify simple "dry years" to more complex drought indicators to identify drought events. Thereby, we want to answer the following key research questions:

- How frequent are recurrent events on the IP?
- Is the identification of recurrent events dependent on chosen datasets and/or indices?
- Are recurrent events triggered by precipitation deficits in a specific season?

With this aim, we first identify historical individual drought events based on the Effective Drought Index (EDI; Byun and Wilhite, 1999) as well as a simple drought index using precipitation deficit and affected area as measures (DI). Results are compared to the widely used Standardized Precipitation Index (SPI; McKee et al., 1993). In a second step, we analyse the recurrence of these events by employing two newly developed indices: the Recurrent Dry Year Index (RDYI) and the Consecutive Drought Year (CDY) Index. Various observational and reanalysis datasets are analysed to test the applicability and suitability of these indices under present climate conditions. Additionally, we perform a careful regional assessment of the vulnerability of the IP to recurrent extreme drought events. The potential impact of ongoing climate change on recurrent drought events in IP is addressed in a follow-up study (Part II, Moemken et al., 2022).

The paper is structured as follows: Chapter 2 describes the methodology and the used datasets. Chapter 3 focusses on the results, while a summary and discussion concludes this paper in chapter 4.

2. DATA AND METHODS

2.1 OBSERVATIONAL DATASETS AND REANALYSES

A set of reanalyses and gridded observational datasets is analysed in this study (***Table 1***). All datasets provide daily precipitation sums at different spatial resolutions. The first dataset is the ensemble version of E-OBS: V20e (Haylock et al., 2008; Cornes et al., 2018), which is considered at two different spatial resolutions (0.1° and 0.25° regular grid) for the period 1950–2018. The second dataset is IBERIA01 (Herrera et al., 2019), which covers the whole IP at a 0.1° regular grid for the period 1971–2015 and is based on a dense network of stations in Portugal and Spain.

The analysed reanalysis ERA5 (Hersbach et al., 2020) is the successor of ERA-Interim (Dee et al., 2011) and is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). We use ERA5 at a regular 0.25° grid for the period 1979–2018. Finally, we consider a COSMO-CLM (CCLM; Rockel et al., 2008) simulation driven with ERA-40 and ERA-Interim boundary conditions

DATA	RESOLUTION		TIME
E-OBS V20e	0.25° (reg)	daily	1950–2018
	0.1° (reg)	daily	1950–2018
IBERIA01	0.1° (reg)	daily	1971–2015
ERA5	0.25° (reg)	daily	1979–2018
ERA MiKlip	0.22° (rot)	daily	1961–2016

Table 1 Overview on used datasets, including information on spatial and temporal resolution as well as available time period.

for 1961–2016. This simulation was performed for the MiKlip project (Marotzke et al., 2016) and was extensively evaluated by Feldmann et al. (2019) and Reyers et al. (2019). It is available on a rotated 0.22° grid (hereafter ERA MiKlip). Given that the datasets cover different time periods, this study focusses on the common period 1981–2015 to ensure comparability.

All analyses are done for the Iberian Peninsula at 10°W-3°E and 36°N-44°N (***Figure 1a***) as defined by Christensen and Christensen (2007; PRUDENCE region 2). Only grid points over land are considered. Some sections focus exemplarily on five Iberian sub-regions (***Figure 1b***), namely the Northwestern (IP-NW; 10°W-5°W, 40°N-44°N), the Northeastern (IP-NE; 5°W-0°E, 40°N-44°N), the Southwestern (IP-SW; 10°W-5°W, 36°N-40°N), the Southeastern (IP-SE; 5°W-0°E, 36°N-40°N), and the Eastern area (IP-E; 0°E-3°E, 38°N-44°N).

2.2 DROUGHT INDICES

We use several indices to identify and characterize historical (recurrent) drought events in the IP. All indices are relative measures in the sense that they indicate deviations from the local long-term precipitation climatology. Here, we consider the period 1981–2010 as climatological reference. All analyses are done for the hydrological year (1st October to 30th September), while some also focus on the individual seasons winter (DJF), spring (MAM) and autumn (SON). Please note that the summer months JJA are explicitly not considered separately, as there is very limited to no significant rainfall over most of Iberia during this time of year (seasonal drought). Throughout this study, we always refer to the hydrological year when using terms like year, yearly, or annual.

Individual drought events

The Drought Index (hereafter DI) is a one-dimensional index, based on the precipitation deficit for a given season

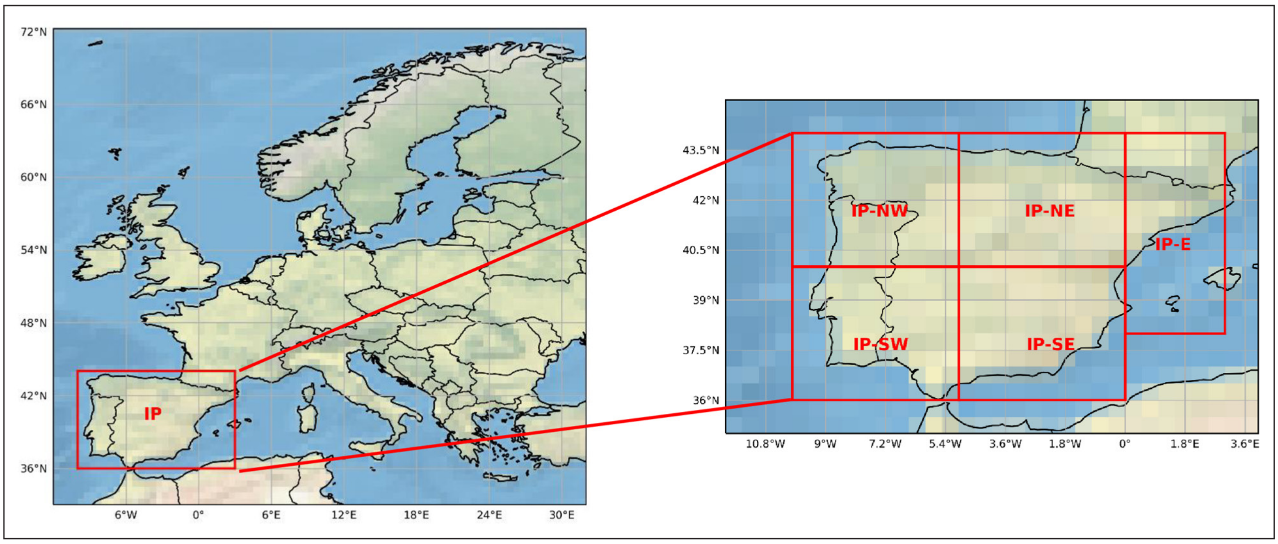

Figure 1 Iberian Peninsula (IP; PRUDENCE region 2; 10°W-3°E, 36°N-44°N) and sub-regions: IP-NW (10°W-5°W, 40°N-44°N), IP-NE (5°W-0°E, 40°N-44°N), IP-SW (10°W-5°W, 36°N-40°N), IP-SE (5°W-0°E, 36°N-40°N), and IP-E (0°E-3°E, 38°N-44°N).

(with respect to climatology) and the affected area. Feio and Henriques (1986) defined an extreme drought year over Portugal as one with a precipitation amount below 60% of the annual average. In accordance, we apply the following two criteria to identify individual drought events for the whole IP:

- Annual (seasonal) precipitation sum less than 65% (50%) of the climatological mean, and
- At least 10% (20%) of all grid points affected by annual (seasonal) precipitation deficit.

The index allows to analyse both the extent (number of grid points with precipitation deficit above threshold) and the intensity (relative precipitation deficit at affected grid points) of the individual drought events. The highest intensity is given for the lowest precipitation ratios (largest precipitation deficit). Extreme events are therefore typically characterized by a large extent and a high intensity.

Additionally, we use the Effective Drought Index (EDI; Byun and Wilhite, 1999). This index can assess both short- and long-term droughts (Byun and Kim, 2010), and correlates well with modelled soil moisture. It considers the daily precipitation accumulation of the last 365 days with a weighting function (effective precipitation) for any given time at every grid point and is measured in standard deviation. Due to a standardization, humid and arid regions fall within the same category, which makes the index applicable worldwide (Europe: Khodayar et al., 2015; Asia: Kim and Byun, 2009; Australia: Deo et al., 2017; USA: Byun and Wilhite, 1999). Please refer to Byun and Wilhite (1999) for a detailed description of the calculation steps. Following Khodayar et al. (2015), we use the below-mentioned categories to classify dry/drought periods. The value in brackets indicates the average probability of occurrence for each of the individual categories.

- Normal: $1.0 > EDI > -1.0$ (80.1%)
- Dry: $-1.0 \geq EDI > -1.5$ (9.8%)
- Severe dry: $-1.5 \geq EDI > -2.0$ (1.7%)
- Extreme dry: $EDI \leq -2$ (0.04%)

A drought year is identified, if EDI is below –1.0 (dry day) on a minimum of 90 days per year (corresponding to one season). These 90 days do not necessarily need to be consecutive.

Results for single drought events are evaluated against the widely (operationally) used Standardized Precipitation Index (SPI; McKee et al., 1993). SPI is calculated from monthly precipitation data. Like EDI, it is a centred, symmetric and normalized index, so that wet and dry climates are described in a similar way. SPI characterizes meteorological droughts at various timescales (from 1 month up to 60 months), which correspond to the availability of different water resources (from soil moisture to reservoir storage). In our study, we use the 3-month SPI (SPI-3) to quantify seasonal drought and the 12-month SPI (SPI-12) for annual drought, respectively. We follow McKee et al. (1993) for the definition of drought categories. As for EDI, the value in brackets specifies the average probability of occurrence for each of the categories. Please note that the missing percent are attributed to the corresponding "wet" categories.

- Mild drought: $0.0 > SPI > -1.0$ (34%)
- Moderate drought: $-1.0 \geq SPI > -1.5$ (9.2%)
- Severe drought: $-1.5 \geq SPI > -2.0$ (4.4%)
- Extreme drought: $SPI \leq -2.0$ (2.3%)

A year is classified as a drought year if SPI-12 values of less than –0.5 are reached.

Recurrent events

To assess the recurrence of dry/drought events in consecutive years, we developed a new set of indices to identify their maximum duration and frequency. These indices are analogue to the Consecutive Dry Days (CDD) concept as defined in the "Expert Team of Climate Change Detection Indices" (ETCCDI; van Engelen et al. 2008; Zhang et al., 2011). A minimum of two consecutive dry/drought years is required for an event to be classified as recurrent.

The first index is the Recurrent Dry Year Index (RDYI), which determines the maximum number of consecutive dry years in a given period (here 34 hydrological years) at every single grid point in the domain. A dry year is identified if the annual precipitation amount is less or equal to 65% of the climatological mean. A sequence of two or more consecutive dry years ($RDYI \geq 2$) is called a dry year period. The frequency index NDYP assesses the number of dry year periods within the given period.

The second index is the Consecutive Drought Year Index (CDY and CDY-EDI). It counts the largest number of consecutive drought years, identified by one of the above-mentioned criteria (DI or EDI), per specified time period. Additionally, the frequency index Number of Drought Periods (NDP and NDP-EDI) with CDY (CDY-EDI) ≥ 2 is calculated. Please note that CDY (NDP) is a one-dimensional index due to the definition of DI and provides only one value for whole IP/each sub-region, whereas CDY-EDI (NDP-EDI) is a two-dimensional index and allows a spatial analysis. In order to directly compare both indices, we also use spatially averaged CDY-EDI (NDP-EDI). For comparison and evaluation, we also calculate CDY and NDP based on drought years defined by SPI-12 (hereafter CDY-SPI and NDP-SPI).

3. RESULTS

3.1 EVALUATION OF THE HISTORICAL DATASETS

In a first step, we evaluated and discussed the performance of the different datasets in terms of precipitation fields. ***Figure 2*** shows the climatology of annual precipitation sums for the hydrological year, computed for 1981–2010. Overall, the five datasets show similar spatial patterns: Highest precipitation values (up to 1800 mm/year) are found along the Northern and Northwestern coast of Iberia, while lowest values are typically depicted in Southeastern Iberia, in the region of Murcia. In this area, values drop below 300 mm/year in the long-term mean for some datasets. Nevertheless, the individual datasets differ considerably in some regions, especially over complex topography (e.g. Galicia, Pyrenees), where discrepancies are as high as 800 mm/year. In general, these deviations seem to result from the different spatial resolutions, with E-OBS 0.1° (***Figure 2b***) and IBERIA01 (***Figure 2c***) depicting much finer spatial structures compared to the other datasets.

Next, the mean annual cycle of both monthly precipitation sums and the number of dry days (precipitation below 1 mm) per month is analysed for 1981–2010. The temporal evolution throughout the year is analysed as spatial mean for whole IP (Supplementary Figure S1). Regarding the annual cycle of precipitation (Figure S1a), all datasets agree on a similar temporal evolution, with a "rainy season" during the winter half and a "dry season" during the summer months, as expected from the dominant Mediterranean climate conditions. All datasets reveal a higher intra-annual variability for Western IP, with highest variations in IP-NW (not shown). Differences between the datasets are found in terms of magnitude (up to 40 mm per month). Here, largest (lowest) values are often identified for IBERIA01 (ERA MiKlip). Regarding the number of dry days (Figure S1b), the values are highest in July and August, and lowest in November. Overall, the datasets agree quite well regarding the precipitation patterns. Nevertheless, some quantitative differences can be observed, e.g. in regions with complex topography. This might also influence the identified drought events in the remainder of this study.

3.2 DROUGHT CHARACTERISTICS OVER IBERIA

In the next step, we focused on the occurrence of individual drought events in Iberia for the period 1981–2015. ***Figure 3*** shows time series of drought events as identified by DI (both extent and intensity), EDI, and SPI-12 for whole IP. Drought events in consecutive years are marked by grey horizontal bars. Overall, DI identifies five to 11 events during the 35-year period, depending on the region and the analysed dataset. Some of these events occur in consecutive years. The largest number of drought events can be found for the ERA MiKlip dataset (red), independent of the considered region. This is especially striking in Eastern IP (not shown), where over twice as many events are identified compared to the other datasets. Generally, droughts occur more frequent in the western parts of IP and show a larger spatial extension in the southern half of IP (not shown). The various datasets differ in terms of drought extent and intensity.

Figure 3c illustrates time series of the spatially averaged number of EDI dry days (EDI < –1.0; section 2.2) per classified drought year (at least 90 days with EDI < –1.0) for whole IP. The different sub-regions are depicted in Figure S2. Compared to the number of dry days in all years (Figure S3), the threshold of 90 dry days seems reasonable in order to filter drought events from the EDI time series. Overall, 10 to 13 drought events are identified for IP and its sub-regions for the 1981–2015 period based on EDI. When compared to DI, the EDI drought event time series agree well for Southern and Western IP, while some discrepancies are found for Eastern IP (not shown). For this area, the EDI criteria typically identifies a larger number of drought events. This is also reflected in

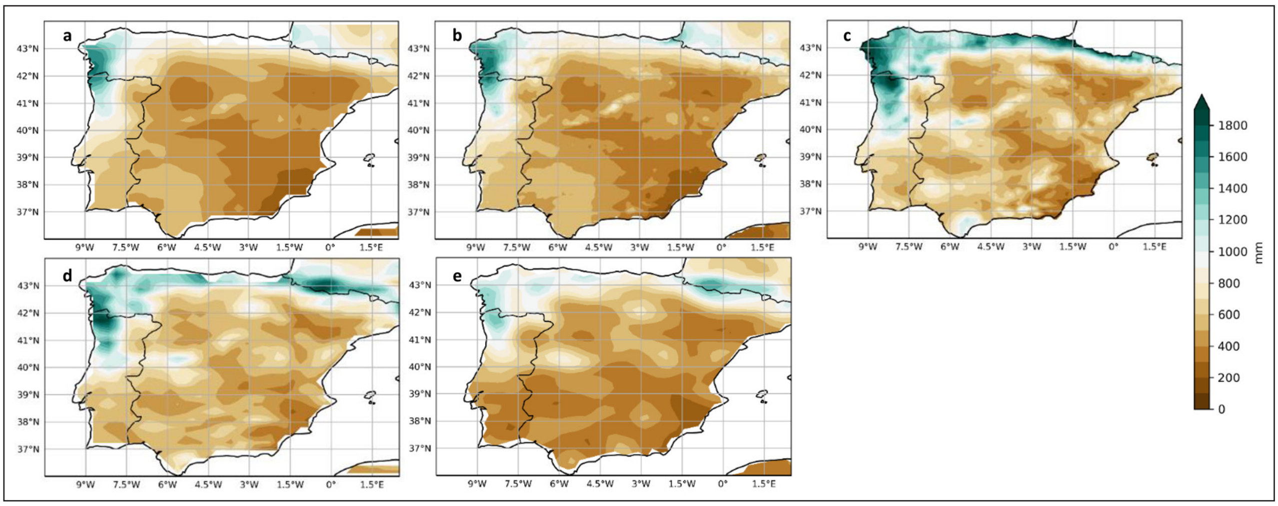

Figure 2 Climatology of annual precipitation sums (in mm) for the hydrological years of the period 1981–2010, i.e. hydrological years 1981/1982 – 2009/2010: (a) E-OBS V20e 0.25°, (b) E-OBS V20e 0.1°, (c) IBERIA01, (d) ERA5, (e) ERA MiKlip.

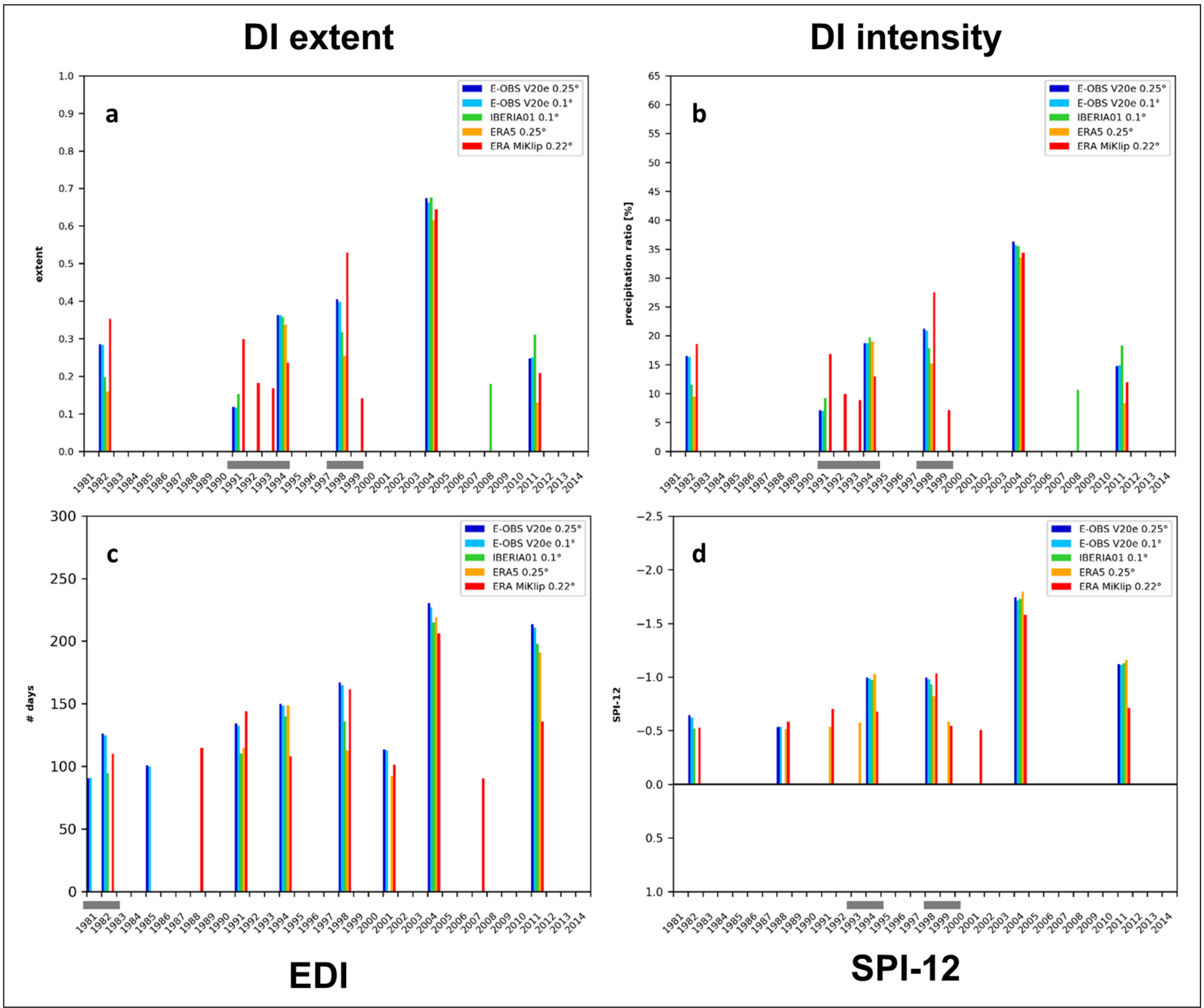

Figure 3 Time series of drought years for the period 1981/1982 – 2014/2015, defined by (a) drought index (DI) extent, (b) DI intensity, (c) EDI, and (d) SPI-12. Depicted are spatial means for IP. The grey horizontal bars indicate consecutive drought years. Please note the inverted y-axis for SPI-12.

the correlation values (between drought year time series based on DI/EDI; not shown), which range between 0.3 (for IP-E in IBERIA01) and 1 (for IP-SW in E-OBS 0.25°).

The time series of spatially averaged SPI-12 values (***Figures 3d*** and S4) show a similar course, with five to 10 identified drought years, depending on the dataset and region. Results show that the IP is regularly hit by at least mild droughts (SPI-12 < 0.0; see Figure S5), which sometimes do occur in successive years. In addition, the time series reveal that the drought intensity may increase for recurrent events. Comparable to EDI, a larger number of single events is found for Northern IP, while the duration of recurrent events is longer in Southern IP (cp. Figures S2 and S4).

In summary, the selected indices are found suitable to detect individual drought events over the IP. All major drought events like 1998/1999, 2004/2005 (García-Herrera et al., 2007) or 2011/2012 (Trigo et al., 2013) are captured, in all regions and for all datasets. The indices prove that droughts are a common phenomenon in IP, especially in the southern regions, with approximately three events per decade. All indices confirm that droughts sometimes do occur in consecutive years. In general, more events are identified when using EDI or SPI, particularly for Northeastern IP. Differences between the various datasets are typically smaller for EDI than for DI or SPI. Overall, results for DI and EDI are comparable to the widely used SPI – both indices are therefore found suitable for the identification of recurrent events in the next step.

3.3 RECURRENCE OF DROUGHT EVENTS

The recurrence of drought events for IP is now investigated for the period 1981–2015. ***Figure 4*** shows the recurrent dry year index (RDYI) for the different datasets. The corresponding frequency index NDYP is depicted in Figure S6. No dry years are identified along the northern border of IP (grey), which corresponds to the regions with the highest annual precipitation amounts (cf. ***Figure 2***). Most of IP is affected only by individual events (blue areas). Accordingly, the NDYP is mostly zero (see widespread grey areas in Figure S6). Regions with two to three consecutive dry years (green coloured) can be found in IP-SE (e.g. around Murcia) and in Northern Portugal. Here, the identified dry periods are 1980–1983 (Murcia), and 2003–2005 and 2007–2009 (Northern Portugal). NDYP reaches a value of three only in small areas (again around Murcia and Northern Portugal), i.e. three dry year periods lasting at least two years. The different datasets agree on the widespread occurrence of individual dry years, but differ in terms of consecutive events. The lowest RDYI numbers are found for E-OBS 0.25° and ERA5 (datasets with coarsest resolution), while they reach values of four for ERA MiKlip (e.g. in Central Spain, yellow areas).

The number of consecutive drought years based on DI (CDY) is illustrated in ***Figure 5*** (top row). Given that CDY is a one-dimensional index, a grid point-wise analysis is not possible. As for RDYI, most parts of IP are affected by

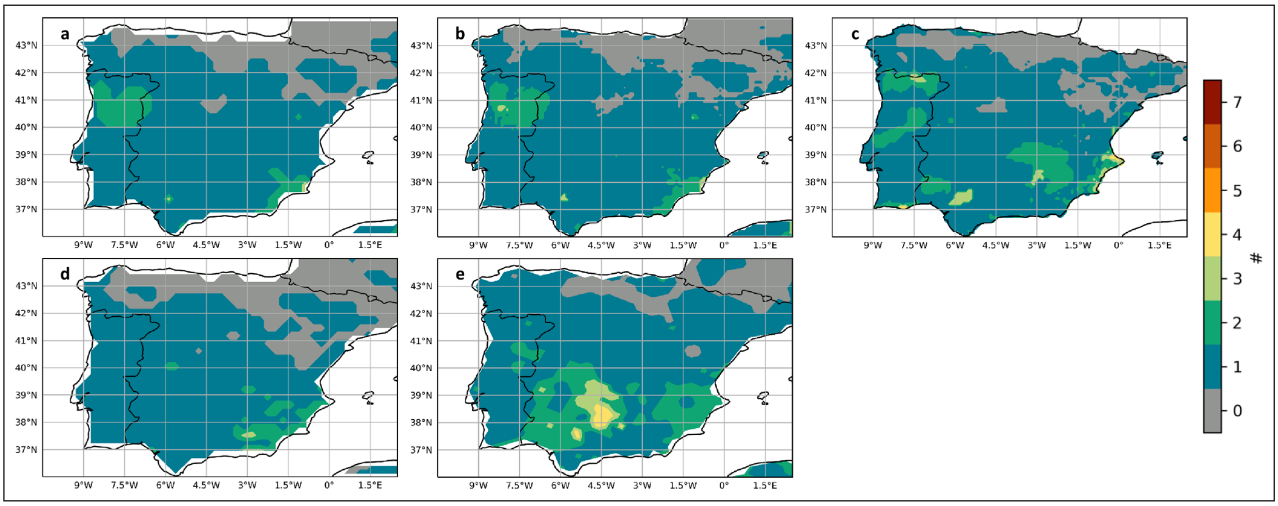

Figure 4 Recurrent dry year index (RDYI) for the hydrological years of the period 1981/1982 – 2014/2015: (a) E-OBS V20e 0.25°, (b) E-OBS V20e 0.1°, (c) IBERIA01, (d) ERA5, (e) ERA MiKlip.

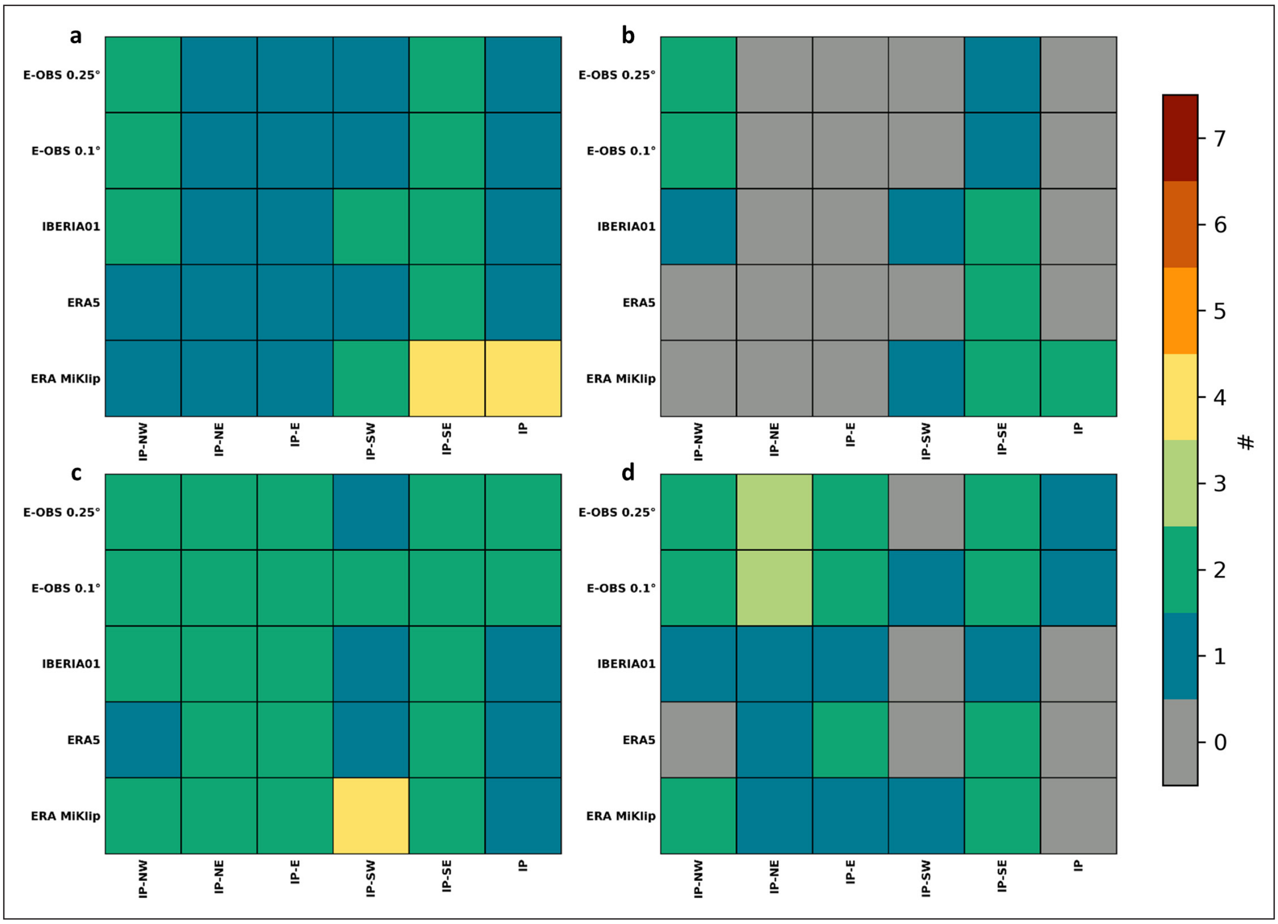

Figure 5 Consecutive drought year index (CDY; left) and number of drought periods (NDP; right) for all datasets and the six regions (IP-NW, IP-NE, IP-E, IP-SW, IP-SE, and IP). First row: based on DI; second row: based on EDI. For definition of sub-regions please refer to Figure 1.

single drought events (blue boxes in ***Figure 5a***), resulting in the occurrence of no recurrent drought periods (NDP=0; grey boxes in ***Figure 5b***). The western and southern parts of IP show at least two consecutive events, depending on the dataset. Again, the ERA MiKlip data stands out as it identifies only individual events for Northern and Eastern IP, but four consecutive drought events (yellow coloured) for IP-SE and whole IP.

Compared to CDY, the number of consecutive drought events identified using EDI (CDY-EDI; ***Figure 5c***) is generally higher. Most regions are affected by two consecutive events, with exception of IP-SW and IP, where only single events are found (e.g. IBERIA01 and ERA5). Thus, most areas show at least one drought period (NDP-EDI; ***Figure 5d***) during the 35-year time span. ERA MiKlip features four consecutive events (twice as much as any of the other datasets), this time for Southwestern IP. A grid point-based view of CDY-EDI and NDP-EDI for the different datasets is given in ***Figures 6*** and S7, respectively. Compared to RDYI/NDYP (***Figures 4*** and S6), the spatial patterns are generally much more heterogeneous and have a finer structure. Unlike CDY, all regions and datasets feature at least one drought event for 1981–2015. Nearly all of IP is affected by at least two consecutive drought years (dark green colours in ***Figure 6***), while single events (blue) can be found only in Southwestern IP (e.g. IBERIA01 and ERA5) and small areas in Spain. Both E-OBS datasets show regions with up to six consecutive drought years (dark orange), e.g. in Central Spain and Northern Portugal. The number of drought periods (NDP-EDI; CDY-EDI ≥ 2) ranges mostly between one and three (Figure S7). In Northern Portugal and Northeastern Spain, up to five drought periods are identified, especially in the E-OBS datasets.

For most of the datasets, CDY-SPI (***Figure 7***) and NDP-SPI (Figure S8) show similar spatial patterns as their EDI counterparts. Most of IP features a minimum of two consecutive drought years (dark green) and consequently at least one drought period (blue). The areas affected only by single drought events (and therefore no drought periods)

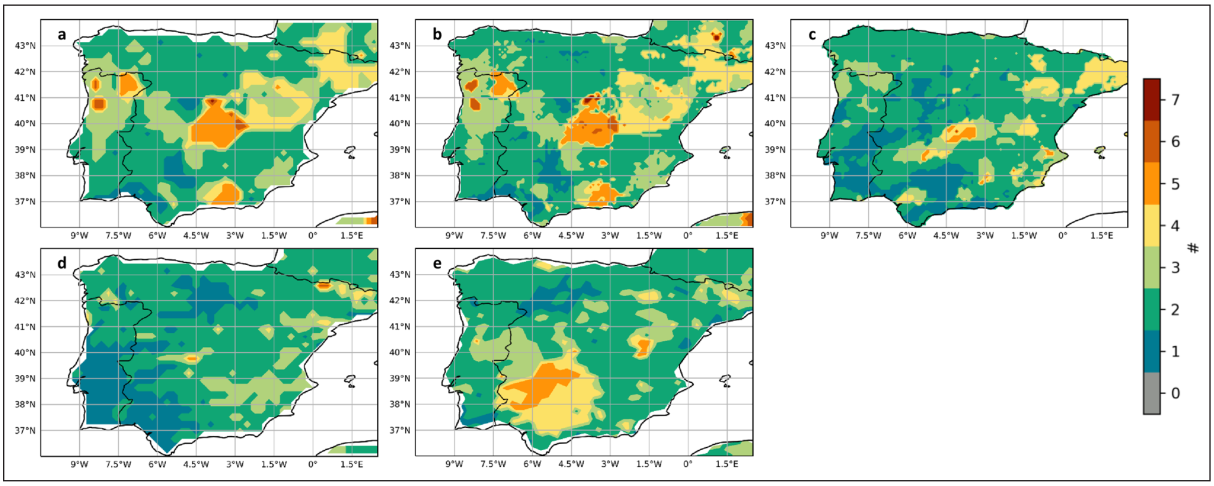

Figure 6 Consecutive drought year index based on EDI (CDY-EDI) for the hydrological years of the period 1981/1982 – 2014/2015: (a) E-OBS V20e 0.25°, (b) E-OBS V20e 0.1°, (c) IBERIA01, (d) ERA5, (e) ERA MiKlip. A drought year is identified, if EDI < –1.0 on at least 90 days per year (see also ***Figure 3***).

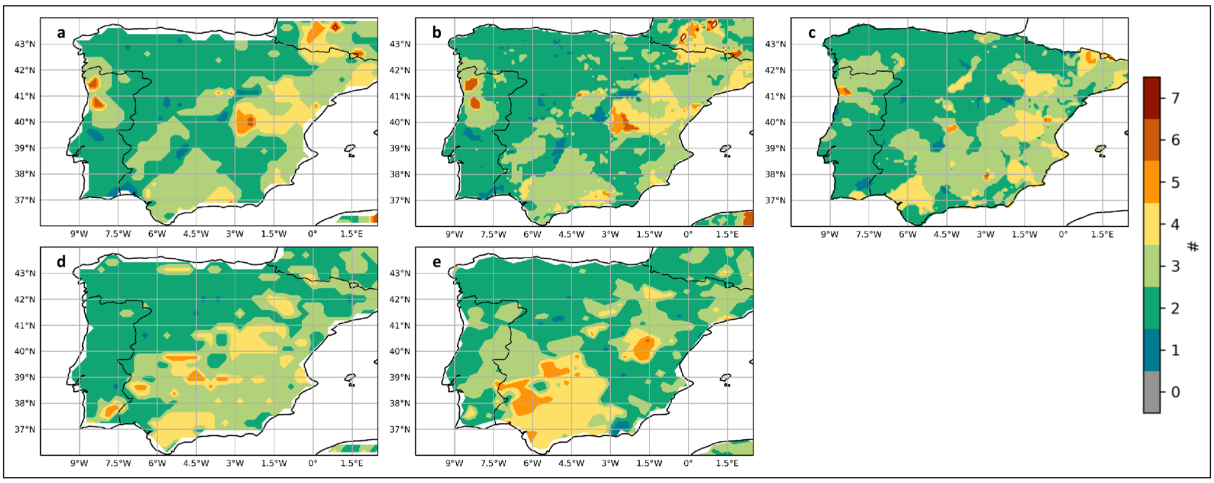

Figure 7 Consecutive drought year index based on SPI (CDY-SPI) for the hydrological years of the period 1981/1982 – 2014/2015: (a) E-OBS V20e 0.25°, (b) E-OBS V20e 0.1°, (c) IBERIA01, (d) ERA5, (e) ERA MiKlip. A drought year is identified, if SPI-12 < –0.5 (see also ***Figure 3***).

are smaller compared to CDY-EDI/NDP-EDI. Large parts of IP are rather hit by three (light green) or four (yellow) consecutive drought years, especially in ERA5 and ERA MiKlip. Like the EDI-based index, CDY-SPI can reach up to six years (dark orange) in small areas in the E-OBS datasets.

In general, the number of identified recurrent dry/drought events depends on the applied index. Typically, lowest numbers are found for RDYI, while highest numbers are depicted for CDY-EDI and CDY-SPI. This agrees well to the results for individual drought events (larger number of EDI events compared to DI events). In addition, the results show a strong dependence on the chosen dataset. Here, results differ not only in terms of magnitude (e.g. lowest numbers generally in ERA5, except for CDY-SPI), but also in terms of affected region (both extent and location). As for single drought events, results for DI and EDI are largely comparable to the widely used SPI in terms of recurrent events.

3.4 SEASONAL PERSPECTIVE

So far, all analyses focused on full hydrological years. However, a seasonal analysis is very important, as droughts can (or not) occur in consecutive seasons, thereby potentially strengthening (balancing) previous precipitation deficits and thus enhancing (mitigating) the negative influence of recurring events. Focus is given to individual seasons which are especially prone to droughts, and the question whether recurrent events are always triggered by individual drought events in a specific season (e.g. winter). ***Figure 8*** shows the seasonal contribution (in percent) to the annual number of EDI dry days for the identified drought years in the period 1981–2015 for the whole IP. The other regions are depicted in Figures S9 (SON), S10 (DJF) and S11 (MAM), respectively. Additionally, ***Figure 8*** displays the time series of spatially averaged SPI-3 for the drought years identified with SPI-12. In general, the individual drought events seem to be mostly caused by a lack of precipitation during winter and spring. Here, the percentage of dry days (EDI) and the drought intensity (SPI-3) is typically higher than for autumn. This behaviour is visible in all sub-regions, with the Southern IP being more affected by precipitation deficits in spring (see Figure S11) than the Northern regions. One example is the 2011/2012 event in IP-SW, which is characterized by a medium (high) number of dry days during winter (spring). This agrees well to the temporal evolution shown in Caldeira et al. (2015; their Figure 1). The influence of autumn precipitation is only evident for individual drought events, like 1985/1986. The pattern is different when looking at drought extent per season for the identified drought events based on DI (not shown): In most cases, the precipitation deficits in autumn and winter are apparently more important than those in spring. The largest drought extent is typically depicted in winter for all sub-regions.

Given the above, we conclude that drought events in Iberia are mostly triggered by a precipitation deficit during the winter half year. The most extreme events, like e.g. 2004/2005, are characterized by a large number of dry days and a high drought intensity, and therefore below-normal precipitation over all seasons. Drought events based on DI and EDI/SPI differ in terms of the importance of spring and autumn precipitation. This may result from the EDI/SPI definition, where information of the previous seasons are incorporated in the calculation (see chapter 2.2).

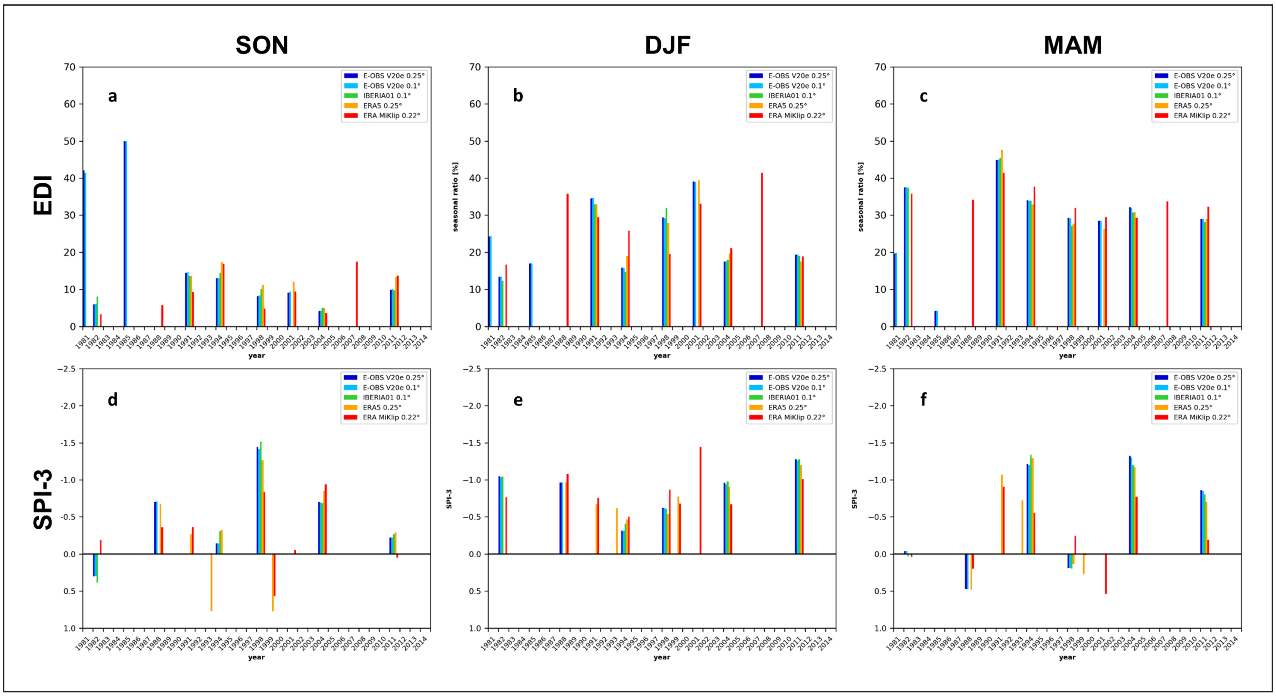

Figure 8 Seasonal ratio (in %) of annual number of dry days (EDI < –1.0) for the drought years identified with EDI (top row). Time series of SPI-3 for drought years identified with SPI-12 (bottom row). Depicted are spatial means for IP for the period 1981/1982 – 2014/2015. First column: SON; Second column: DJF; Third column: MAM.

4. SUMMARY AND DISCUSSION

In this study, we introduce a new set of indices to analyse the recurrence of meteorological drought events in the Iberian Peninsula. The applicability of these indices for present climate conditions is evaluated by using different observational and reanalysis datasets. The main conclusions with respect to the key research questions are as follows:

- Our analysis shows that extreme droughts are a common feature of the Iberian climate, with roughly three individual events per decade. Moreover, some regions (especially in Southern and Central IP) are vulnerable to recurrent drought events. The length of these recurrent events is typically two or three years, but may reach six consecutive years.
- The chosen indices are suitable to detect the major historical events like the 1998/1999 or the 2004/2005 drought in all datasets. However, some sensitivity was identified regarding the choice of dataset and index. First, an enhanced number of events is identified in datasets with higher resolution (E-OBS 0.1° vs 0.25°). Second, the number of identified droughts is larger for EDI and SPI than for DI, leading to systematic differences in both the duration and frequency of recurrent events.
- Our results show that (recurrent) droughts are primarily driven by precipitation deficits in the winter half year. Precipitation deficits in the winter months (DJF) trigger both EDI/SPI and DI events, while deficits during spring (autumn) are more important for the former (latter). The most extreme events (e.g. 2004–2005) are typically characterized by reduced precipitation in all seasons.

While the statement that droughts are a common phenomenon in the IP is not an unexpected result (see e.g. García-Herrera et al., 2007; Coll et al., 2017), the current study provides a first estimate of drought recurrence in the region. We are able to show that drought events in IP do occur in consecutive years. In doing so, we extend the findings from past studies (e.g. Páscoa et al., 2017; Spinoni et al., 2017) and show that an increase in drought frequency and/or duration may result in the recurrence of drought events in successive years. However, recurrent events are usually not frequent – at least under present climate conditions. This is in agreement with previous studies like Spinoni et al. (2015b) or Coll et al. (2017), who – while using different indices and focussing on individual droughts – indicate the occurrence of drought in consecutive years, particularly in the last decades.

The application of different drought indices aimed at the consideration of various aspects of drought and related impacts. One notable difference is the higher sensitivity of both EDI and SPI for the identification of droughts compared to DI, and this effect obviously "propagates" to the quantification of recurrent drought events. In particular, the spatial structure of the indices differs considerably, as EDI/SPI reveal finer spatial structures and larger spatial heterogeneities than DI for exactly the same dataset. One possible reason could be the "memory effect" of EDI, which results from the incorporation of (weighted) information of the last 365 days – and thus information of the previous seasons – in the calculation. This effect could also mean that EDI is less strongly influenced by inter-annual variability compared to DI. The same applies to SPI, where information from the previous year is considered in the calculation of SPI-12. This would also explain why the results of EDI and SPI match each other better than those of EDI/SPI and DI. Another reason could be the choice of threshold values for calculating DI and RDYI (annual precipitation amount < 65% of climatological mean): These may be chosen too high, which means that less severe droughts are not taken into account and thus fewer recurrent events are identified. At the same time, these thresholds should not be set too low, as otherwise the indices would not appear suitable for climate change studies – in particular considering the projected drying trends (see also Moemken et al., 2022). The main difference between EDI and SPI lies in the usage of daily compared to monthly precipitation values. By considering daily data, EDI takes into account the aggravating effects of runoff and evapotranspiration, which build up over time (Byun and Wilhite, 1993). This might be an advantage of EDI over SPI for ecosystem impact studies.

All indices used in this study are based on precipitation only. There are several reasons for this choice: For one, all indices should be suitable for being applied to large datasets, e.g. large multi-model ensembles of high-resolution regional climate simulations (e.g. Jacob et al., 2014; Berg et al., 2019; Moemken et al., 2022). Indices based on several variables would inevitably limit data availability and at the same time increase the required computing time. On the other hand, indices that take evapotranspiration into account (e.g. SPEI, PDSI) depend heavily on the parameterisation of the latter. Additionally, studies like Milly and Dunne (2017) show that trends of the parameterised evapotranspiration are often overestimated in climate change studies.

The comparatively large number of drought events in the ERA MiKlip dataset compared to E-OBS and IBERIA01 is assumed to be largely associated with the nature of the dataset, as the former is a RCM generated dataset. RCMs (and models in general) have difficulties providing realistic intensity distributions of rainfall, both at the lower ("drizzle effect") and the higher end (e.g. Feldmann et al., 2008; Berg et al., 2012; Ehmele et al., 2020). In practical terms, the enhanced number of drought events seem to be associated with the overall lower precipitation ratios in ERA MiKlip compared to E-OBS and IBERIA01.

In this study, we have focussed on the common period between all datasets to ensure comparability. However, the chosen time period (35 years) may be considered too short for a robust assessment of the recurrence of drought events. Thus, it would be important to extend this evaluation to longer datasets. Good candidates could be the complete E-OBS dataset (currently available for 1920–2019) and other model datasets encompassing the whole 20th century like LAERTES-EU (Ehmele et al., 2020).

One of the known impacts of recurrent drought is its effects on ecosystem resilience and plant-plant interactions (e.g. Caldeira et al., 2015). Recent field work in the region of Southwestern Iberia provided evidence that the effects of recurrent droughts are important but might be strongly non-linear (Haberstroh et al., 2021). Other known effects deal with water availability for the public and agriculture (e.g. Iglesias et al., 2009; Gu et al., 2020). These impacts lead us to the question on how recurrent droughts will be affected by ongoing climate change. Given that the current climate projections suggest a general reduction of total annual precipitation in the region, it is expected that the frequency of drought – and consequently the recurrence of drought – should increase in future decades (e.g. Spinoni et al., 2018; 2020). An increase in recurrent drought risk could have severe implications on both ecosystem and population in the IP and would require the implementation of adaptation strategies to secure water supply in future decades. Within this context, a follow-up study (Part II, Moemken et al., 2022) applies the new recurrent drought indices to the EURO-CORDEX ensemble (Giorgi et al., 2009).

Overall, our study provides novel evidence regarding the recurrence of drought events for the Iberian Peninsula under present climate conditions. The used indices have proved to be suitable for the detection and analysis of such events. In particular, the EDI-based indices have great potential and could easily be applied to other drought-threatened regions around the world.

DATA ACCESSIBILITY STATEMENT

The input data for this study are freely available from

- *https://www.ecad.eu/download/ensembles/download.php* (E-OBS).
- *http://hdl.handle.net/10261/183071* (IBERIA01).
- *https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5* (ERA5; Copernicus Climate Change Service, 2017).

For ERA MiKlip, it is planned to make the data available through the Long-Term Archive (LTA) of the German Climate Computing Center (Deutsches Klimarechenzentrum, DKRZ).

The processed data that support the findings of this study are available from the corresponding author upon reasonable request.

ABBREVIATIONS

CDY	Consecutive Drought Year Index, based on Drought Index
CDY-EDI	Consecutive Drought Year Index, based on Effective Drought Index
DI	Drought Index
DJF	winter months (December, January, February)
EDI	Effective Drought Index
IP	Iberian Peninsula
IP-E	Eastern Iberian Peninsula
IP-NE	Northeastern Iberian Peninsula
IP-NW	Northwestern Iberian Peninsula
IP-SE	Southeastern Iberian Peninsula
IP-SW	Southwestern Iberian Peninsula
MAM	Spring months (March, April, May)
NDP	Number of Drought Periods, based on Drought Index
NDP-EDI	Number of Drought Periods, based on Effective Drought Index
NDYP	Number of Dry Year Periods
RDYI	Recurrent Dry Year Index
SON	Autumn months (September, October, November)
SPI	Standardized Precipitation Index

ADDITIONAL FILE

The additional file for this article can be found as follows:

- **Supplementary file.** Supplementary Figures S1 to S11. DOI: *https://doi.org/10.16993/tellusa.50.s1*

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COMPETING INTERESTS

The authors have no competing interests to declare.

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