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ORIGINAL PAPER

# Recent and future changes of precipitation extremes in mainland Portugal

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**Abstract**
Recent and future changes in precipitation extremes over Portugal were studied. Trends in selected precipitation indices were calculated on a seasonal scale for the period of 1950–2003. Considering the same indices, this study also assessed possible changes under future climatic conditions (2046–2065). Furthermore, trends and projections for the future were evaluated using a single/unified index of extreme precipitation susceptibility (EPSI). The results revealed statistically significant drying trends in spring, mainly in northern and central Portugal, while weak wetting trends were detected in autumn. The EPSI trends also depicted a decrease of extreme precipitation in spring over central Portugal and a slight increase in autumn over northern Portugal and nearby Lisbon. On the other hand, climate change projections revealed a decrease in precipitation, mainly over northwestern Portugal, whereas the contribution of extreme precipitation to total precipitation is expected to increase, mostly in southern Portugal. The maximum number of consecutive dry days (CDD) is also projected to increase throughout Portugal. EPSI showed enhanced susceptibility for most Portuguese municipalities, which may be associated with increased vulnerability to flash floods. Climate change projections by municipality for both EPSI and CDD are an important decision support tool for civil protection and for risk management in Portugal.

## 1 Introduction

Extreme weather events have significant impacts on society, being precipitation extremes as one of the major triggers of natural disasters, such as flash floods, urban inundations, landslides, soil erosion, and crop destruction. Precipitation variability plays an essential role in determining water resources availability, which in turn controls agriculture, river flow and hydropower production, and tourism, as well as other important economic activities for social development (Melo-Gonçalves et al. 2016). According to the Intergovernmental Panel on Climate Change (IPCC), precipitation extremes will continue to increase in both frequency and intensity as a result of climate change and human activities (IPCC 2012). Extreme weather and climate events have received increasing attention in recent years due to the loss of human lives and to increasing costs driven by them (Wang et al. 2017). At the same time, research on climatic trends has significantly widened, particularly for precipitation and temperature (e.g., Aguilar et al. 2005; Alexander et al. 2006; Klein Tank et al. 2006; Booth et al. 2012; Omondi et al. 2014; Deshpande et al. 2016).

On a global scale, the global mean surface temperature increased during the twentieth century and the beginning of the twenty-first century (e.g., Hegerl et al. 2007; Boccolari and Malmusi 2013; Cinco et al. 2014). In effect, the globally mean surface temperature increased by 0.85 [0.65 to 1.06] °C from 1880 to 2012 (IPCC 2013). However, trends in precipitation showed heterogeneous and very complex spatial patterns

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(Bartolini et al. 2018). Overall, on a global scale, a significant wetting trend was detected, whereas the maximum number of consecutive dry days revealed remarkably different regional changes (Frich et al. 2002; Alexander et al. 2006). Most studies using observed precipitation time series indicated an increasing probability of occurrence of extreme precipitation over Europe during the last decades and over the last century (Alexander et al. 2006; Zolina et al. 2008; van den Besselaar et al. 2013). These works are commonly based on indices of extremes that occur on average once (or several times) each year (or season), such as those defined by the Expert Team on Climate Change Detection and Indices (ETCCDI) (van den Besselaar et al. 2013). Several studies showed that changes in extreme precipitation are not necessarily consistent with trends in mean precipitation on either global or regional scales (Wu et al. 2015).

Precipitation extremes are increasing worldwide, even in regions experiencing a reduction or no change in mean precipitation (Trenberth 2011). However, there are regional and seasonal dependencies in these general trends for increasing extreme precipitation. Moreover, climate models cannot overcome some important limitations in the simulation of precipitation and uncertainties in future projections of extreme events are thus still noteworthy, particularly at regional scales with complex physiographic conditions (Keggenhoff et al. 2014). In this way, it is important to analyze changes in extremes of precipitation based on observational data (Keggenhoff et al. 2014). In the Iberian Peninsula, precipitation has strong spatial and temporal irregularity (Trigo et al. 2004). Precipitation trends have been analyzed for different areas of the Iberian Peninsula using weather station data (e.g., Hidalgo-Muñoz et al. 2011; Lima et al. 2013; Espírito Santo et al. 2014; Sáez de Cámara et al. 2015; Merino et al. 2016). For mainland Portugal, Espírito Santo et al. (2014) found statistically significant drying trends in spring and a reduction of extremes. In autumn, wetting trends were detected, though they were not generally significant. Furthermore, Lima et al. (2013) found significant decreasing trends in spring precipitation, while heavy precipitation events in autumn have become more frequent. Lima et al. (2015) showed that several stations revealed predominantly negative tendencies in the occurrence of precipitation extremes, though not statistically significant over the 1941–2007 period.

In addition to the works on trends, the assessment of climate change projections was also carried out for Portugal. Costa et al. (2012), showed significant decreases in total precipitation for 2071–2100, mainly in autumn over northwestern and southern Portugal. Further, the contributions of extreme precipitation events to total precipitation are also expected to increase, mainly in winter and spring over northeastern Portugal. Melo-Gonçalves et al. (2016) demonstrated a decrease in annual precipitation over the Iberian Peninsula, mostly in the north and northwest (up to 400 mm). The maximum number of consecutive dry days was projected to increase until the middle of the twenty-first century all across the peninsula, while R×5day (maximum 5-day precipitation) was projected to decrease during spring and autumn over most of the peninsula.

The motivation for the present study mainly arises from the three following points. First, we aim to continue an earlier work on extreme precipitation in mainland Portugal using a single/unified index of extreme precipitation susceptibility, i.e., EPSI (Santos et al. 2017). Second, the state-of-the-art trend analyses in Portugal have been mostly based on a relatively small number of long-term and homogenized weather station data (e.g., Lima et al. 2013; Santos and Fragoso 2013; Espírito Santo et al. 2014; Lima et al. 2015). Nonetheless, many factors can influence a trend analysis: the dataset (e.g., number of stations, period investigated, and discontinuities), the selection of the precipitation indices, and the methodology applied to estimate the trend (Pryor et al. 2009; Turco and Llasat 2011; Merino et al. 2016). In order to improve our current understanding of the trends on precipitation extremes, a regular grid was used to calculate trends over a period of more than 50 years. This approach provides a robust and spatially coherent assessment of the recent trends on precipitation extremes over mainland Portugal. Third, precipitation plays a major role on water resources and natural hazards, as well as on many socioeconomic sectors and ecosystems. Therefore, the assessment of climate change projections based on a higher spatial resolution than in previous studies is of foremost relevance. For instance, Costa et al. (2012) employed a gridded precipitation dataset (E-OBS) for assessing climate change projections of precipitation extremes in Portugal, but at a coarser spatial resolution and based on a much less dense network of weather stations than herein. Hence, the objectives of the present study are threefold: (1) to investigate historical trends of extreme precipitation indices and EPSI using a homogenized observational gridded dataset; (2) to assess climate change projections for these indices; and (3) to discuss their corresponding potential impacts, mainly on flood and drought occurrences.

## 2 Methodology

### 2.1 Study area

In mainland Portugal, the relief contrast between the northern and southern halves of the country is apparent, being the former region much more mountainous than the latter (Fig. 1). In the northern region, the main mountains are approximately parallel to the coast (north-south oriented), producing an orographic barrier against the moist Atlantic winds (Santos and Fragoso 2013). In this way, the spatial variability of precipitation reflects not only the irregular

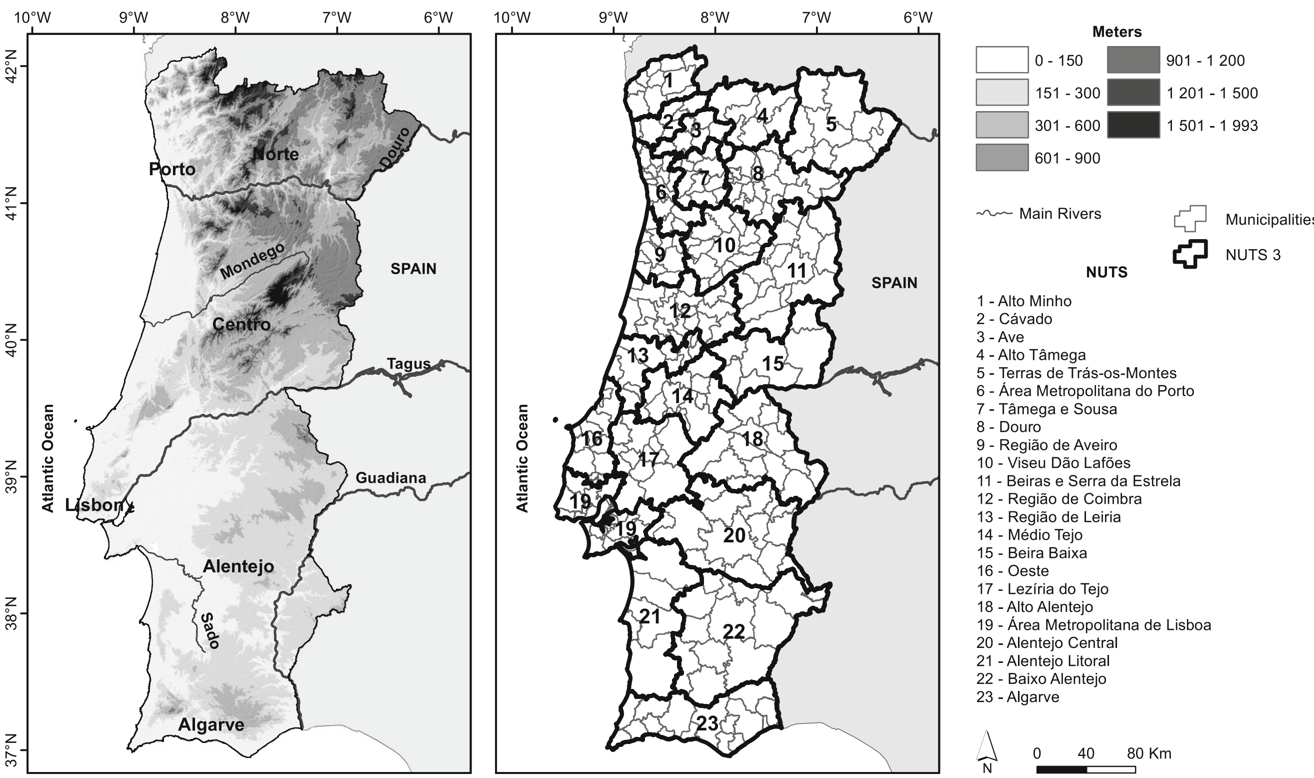


**Fig. 1** **a** Hypsometry of mainland Portugal. **b** Geographical location of the 23 NUTS - Nomenclature of Territorial Units for Statistics - 3 regions (see the list for their designations)

distribution of orography (Santos et al. 2017) but also the proximity to the Atlantic Ocean, the latitudinal location (between the sub-tropical ridge and the sub-polar depression belt), and the role played by teleconnection patterns (e.g., North Atlantic Oscillation and East Atlantic Pattern) or weather types (Santos et al. 2015; Melo-Gonçalves et al. 2016; Santos et al. 2016; Santos et al. 2017).

Precipitation ranges from more than 2000 mm, in the northwest, to roughly 400 mm, in the south-eastern most part of the country (Santos et al. 2017). The temporal irregularity manifests itself by a high frequency of long dry periods interrupted by intense precipitation episodes, which are also expressed by noteworthy flood risks (Merino et al. 2016). Additionally, the precipitation regime presents a very strong seasonality, with a pronounced minimum in summer, a typical feature of Mediterranean-type climates (Santos et al. 2017). About 40% of annual precipitation occurs in winter (December to February), while less than 6% occurs in the summer (June to August) (Lima et al. 2015). The remaining months are transitional periods (Trigo and DaCamara 2000), being still relatively rainy in the northwest, but much drier in the south of the country (Santos et al. 2017).

## 2.2 Precipitation data

In the present study, daily precipitation data on a 0.20° latitude × 0.20° longitude regular grid (spatial resolution of ~ 20 km), originally defined over mainland Portugal and for the period from 1950 to 2003, was retrieved from the PT02 dataset (Belo-Pereira et al. 2011). The use of gridded data, with a regular coverage of the territory, is more adequate for comparison with climate model outputs than station/site data. This precipitation dataset is based on 188 meteorological stations from the Portuguese Meteorological Service (IPMA) and on 618 rain gauges from the Portuguese Environmental Agency (APA) (Belo-Pereira et al. 2011).

## 2.3 Indices of extremes

The precipitation indices considered in the present study are among those suggested by the ETCCDI (Karl et al. 1999) and have been applied in many climate change research worldwide (e.g., Jones et al. 2013; Keggenhoff et al. 2014; Stephenson et al. 2014; Bennett and Walsh 2015; Supari et al. 2017; Wang et al. 2017).

In this study, eight precipitation indices were chosen (Table 1 and Fig. S1): total precipitation (PRCPTOT), maximum 1-day precipitation (R×1day), maximum 5-day precipitation (R×5day), the simple daily intensity index (SDII), number of heavy precipitation days (R20 mm), consecutive wet days (CWD), consecutive dry days (CDD) and contribution from very wet days to total precipitation (R95PTOT). PRCPTOT corresponds to the total annual precipitation in wet days (precipitation ≥1 mm). The R×1day and R×5day

**Table 1** Definition of the eight precipitation extreme indices used in this study, with the abbreviations used in the text, full name, short definition, and corresponding units

| Abbreviation | Name | Definition | Unit |
|---|---|---|---|
| PRCPTOT | Total precipitation | Annual total precipitation in wet days (precipitation ≥ 1 mm) | mm |
| R×1day | Maximum 1-day precipitation | Annual highest daily precipitation | mm |
| R×5day | Maximum 5-day precipitation | Annual highest 5 consecutive precipitation days | mm |
| SDII | Simple daily intensity index | Annual total precipitation divided by the number of wet days (precipitation ≥ 1 mm) in the year | mm day$^{-1}$ |
| R20 | Number of heavy precipitation days | Annual count of days when precipitation ≥ 20 mm | days |
| CWD | Consecutive wet days | Maximum number of consecutive days with precipitation ≥ 1 mm | days |
| CDD | Consecutive dry days | Maximum number of consecutive days with precipitation < 1 mm | days |
| R95PTOT | Contribution from very wet days | Fraction of annual total precipitation exceeding 95th percentile | % |

describe the precipitation associated with extreme wet spells. SDII reproduces the daily precipitation intensity. R20 corresponds to the amount of wet days with precipitation ≥ 20 mm. CWD is the maximum number of consecutive wet days (daily precipitation ≥ 1 mm), while CDD is the maximum number of consecutive dry days (precipitation < 1 mm). R95PTOT determines the contribution of daily precipitation extremes (precipitation in days with precipitation exceeding the 95th percentile) to total precipitation (Santos et al. 2017).

The extreme precipitation susceptibility index (EPSI) was based on a pre-selection of ETCCDI precipitation indices, namely R×1day, R×5day, SDII, R20, CWD, and R95PTOT. In the present study, susceptibility refers to the probability of any given region being affected by a precipitation-driven disaster, given a set of conditions (Guzzetti et al. 2005). The EPSI corresponds to an equally weighted summation of the aforementioned six indices, previously normalized so that all indices range from 0-minimum to 1-maximum over mainland Portugal. More details on this methodology can be found in Santos et al. (2017). The EPSI was computed on both annual and season timescales where higher values imply a greater propensity to the occurrence of extreme precipitation.

The analysis was carried out at the annual and seasonal scales, due to the aforementioned strong seasonality of the precipitation regime in Portugal: autumn (September–November), winter (December–February), and spring (March–May). As summer precipitation is typically negligible and highly irregular, it was thus discarded from the analysis. The Pettitt test (Pettitt 1979) was applied to detect change-points in the time series at a significance level of 5% (95% confidence).

A comparison with the trends in the North Atlantic Oscillation (NAO) and East Atlantic pattern (EA) teleconnection indices was also carried out. The NAO is one of the main sources of climate variability in the European region and it is characterized by two centers of action of opposite sign in the North Atlantic, one over the Azores and another over Iceland (Hurrell 1995; Gallego et al. 2005; Santos and Corte-Real 2006; Rahimpour Golroudbary et al. 2016). Furthermore, the negative trend in precipitation over Southwestern Europe, including Portugal, has been commonly attributed the strengthening of the NAO positive phase (e.g., Goodess and Jones 2002; Santos et al. 2005; Santos et al. 2006; Pinto and Raible 2012; Fragoso et al. 2015; Sáez de Cámara et al. 2015; Santos et al. 2016). The East Atlantic pattern (EA) is the second leading atmospheric circulation mode governing the variability of the large-scale atmospheric flow over the North Atlantic-European region (Woollings et al. 2011; Comas-Bru et al. 2016). The EA significantly affects precipitation and air temperature variability over Europe (Rodriguez-Puebla et al. 1998; Comas-Bru and McDermott 2014; Comas-Bru et al. 2016).

NAO and EA were calculated based on the daily means of the mean sea level pressure (MSLP) fields (Santos et al. 2018), within an extended Euro-Atlantic sector (20–80° N, 90° W–40° E), and obtained from the NOAA Earth System Research Laboratory – Physical Sciences Division (http://www.esrl.noaa.gov/psd/). Following the same methodologies proposed by Barnston and Livezey (1987), Chen and Van den Dool (2003), and van den Dool et al. (2000), the NAO and EA indices were determined using a principal component analysis on the daily MSLP (latitude's cosine weighted) anomalies with respect to the corresponding long-term daily means (Santos et al. 2018). The NAO index (leading principal component) describes ca. 24% of the total temporal variance, whereas the EA index (second principal component) represents approximately 19% of the variance (Santos et al. 2018).

## 2.4 Trend detection

The nonparametric Mann–Kendall (Mann 1945; Kendall 1976) test, widely adopted for the study of trends in climatic series (e.g., Łupikasza 2010; Río et al. 2011; Booth et al. 2012; Boccolari and Malmusi 2013; Acero et al. 2014; Pakalidou and Karacosta 2017), was also used in this study. The Mann–Kendall test was applied to determine the significance of a trend, while the Sen's slope estimator (Theil 1950; Sen 1968) was used to estimate the magnitude of the detected trends (Supari et al. 2017). The assumption of the null hypothesis, H0, is that the sequence of values occurs independently, while the alternative hypothesis, H1, considers that the data are distributed according to an increasing or decreasing trend (Gallego et al. 2011; Santos and Fragoso 2013). The slope calculated by the Theil–Sen's estimator has been largely applied to either hydrological or climatological time series (e.g., Bartolini et al. 2008; Paulo et al. 2012; Ahammed et al. 2014; Keggenhoff et al. 2014; Santos et al. 2014; Sayemuzzaman et al. 2014). The test was applied at a significance level of 5% and the trend results were mapped using the kriging spatial interpolation.

The 278 municipalities of mainland Portugal were then spatially grouped into different classes based on EPSI and CDD and following the Ward's agglomerative hierarchical clustering method. The dominant EPSI and CDD categories were identified for each class.

## 2.5 Future forcing scenarios

Future projections were also based on gridded daily precipitation totals over mainland Portugal. Data were retrieved from a multi-model ensemble of Regional Climate Model (RCM) – Global Climate Model (GCM) chain simulations, produced within the framework of the EURO-CORDEX project (Giorgi et al. 2004; Jacob et al. 2014). Data were available at

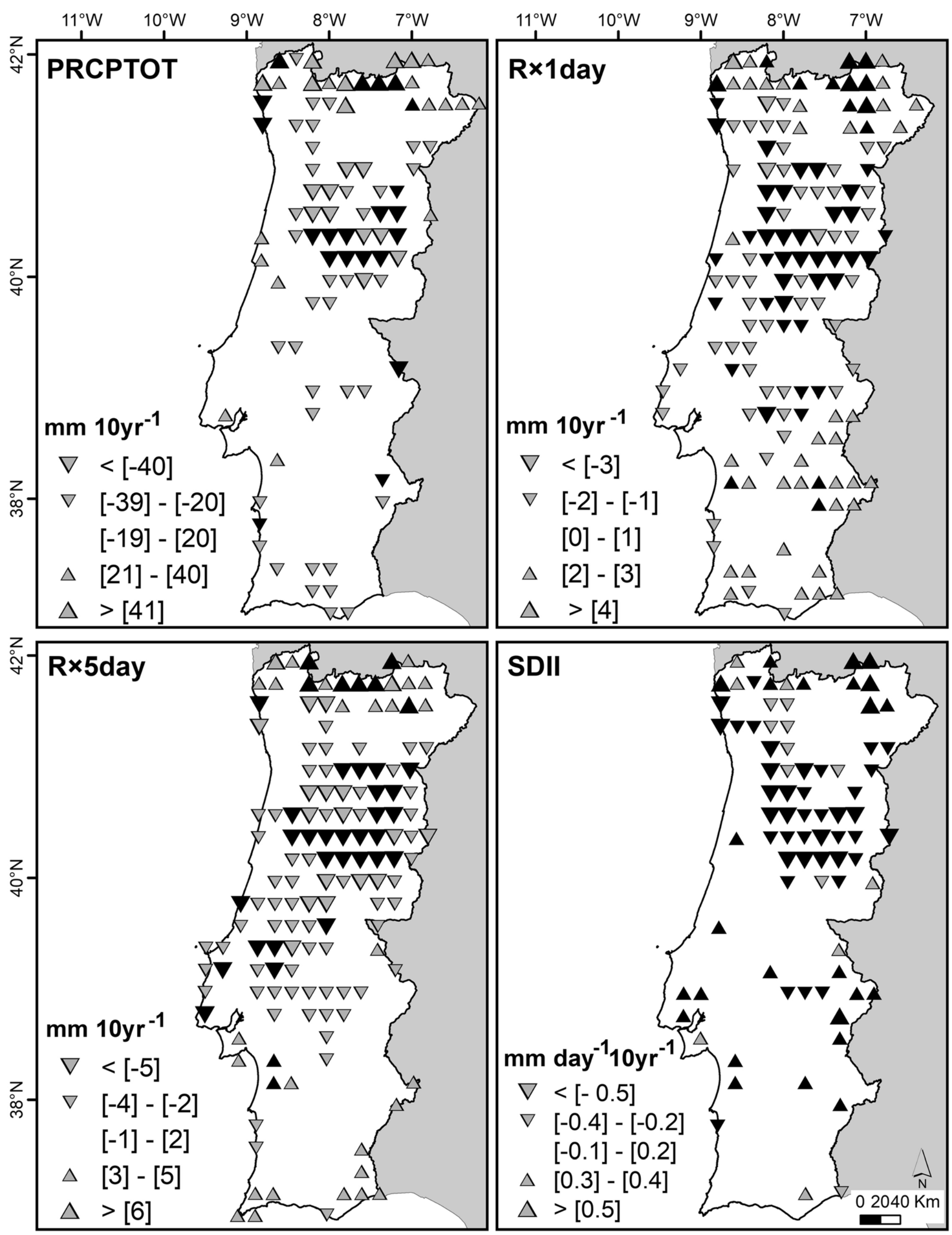


**Fig. 2** Annual trends of PRCPTOT, R×1day, R×5day, SDII, R20, CWD, CDD, and R95PTOT for the period from 1950 to 2003. Triangles represent the Sen's slope per decade. Upward and downward triangles indicate positive and negative trends, respectively. The size of the triangles indicates the magnitude of the trend as identified in the respective legend. Black triangles correspond to statistically significant trends at 5% significance level (Z Kendall's coefficient)

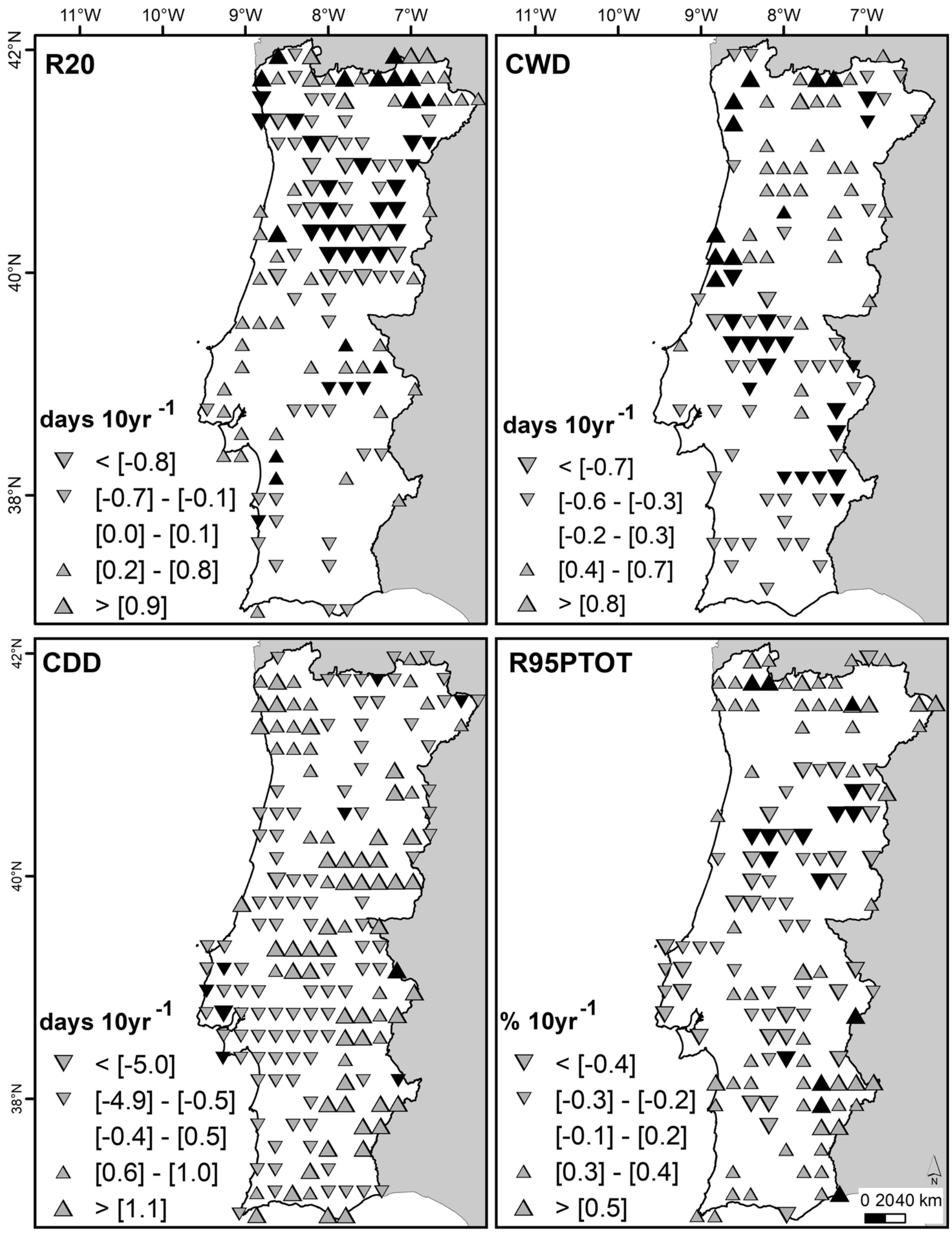


**Fig. 2** continued.

~ 12.5 km spatial resolution. Simulations from seven RCM-GCM pairs were herein selected (Table S1). In EURO-CORDEX, these model chains were generated under the 20C3M forcing over the baseline period of 1986–2005 (20 years). For the future projections, the period of 2046–2065 (20 years) under RCP8.5 was selected (Moss et al. 2010; van Vuuren et al. 2011). Both recent past and future periods have the same length (20 years) for consistency in the analysis. Although other anthropogenic forcing scenarios, such as RCP4.5, may have been chosen, RCP8.5 seems to be more realist at present. Furthermore, a medium-term period was chosen (2046–2065), as it is generally more suitable than shorter or longer term periods, e.g., when planning infrastructures and territory, for decision-making by municipalities, policymakers, and stakeholders.

The nonstationary Cumulative Distribution Function-matching (CDFm) bias correction method, proposed by Miao et al. (2016), which is a recent development from the Quantile Mapping approach (Li et al. 2010; Wang and Chen 2014), was applied to the raw model outputs. This methodology enables correcting the full probability distribution function instead of more conventional methods that correct only biases in first-order statistical moments (e.g., means and/or variances). The observation-based precipitation dataset

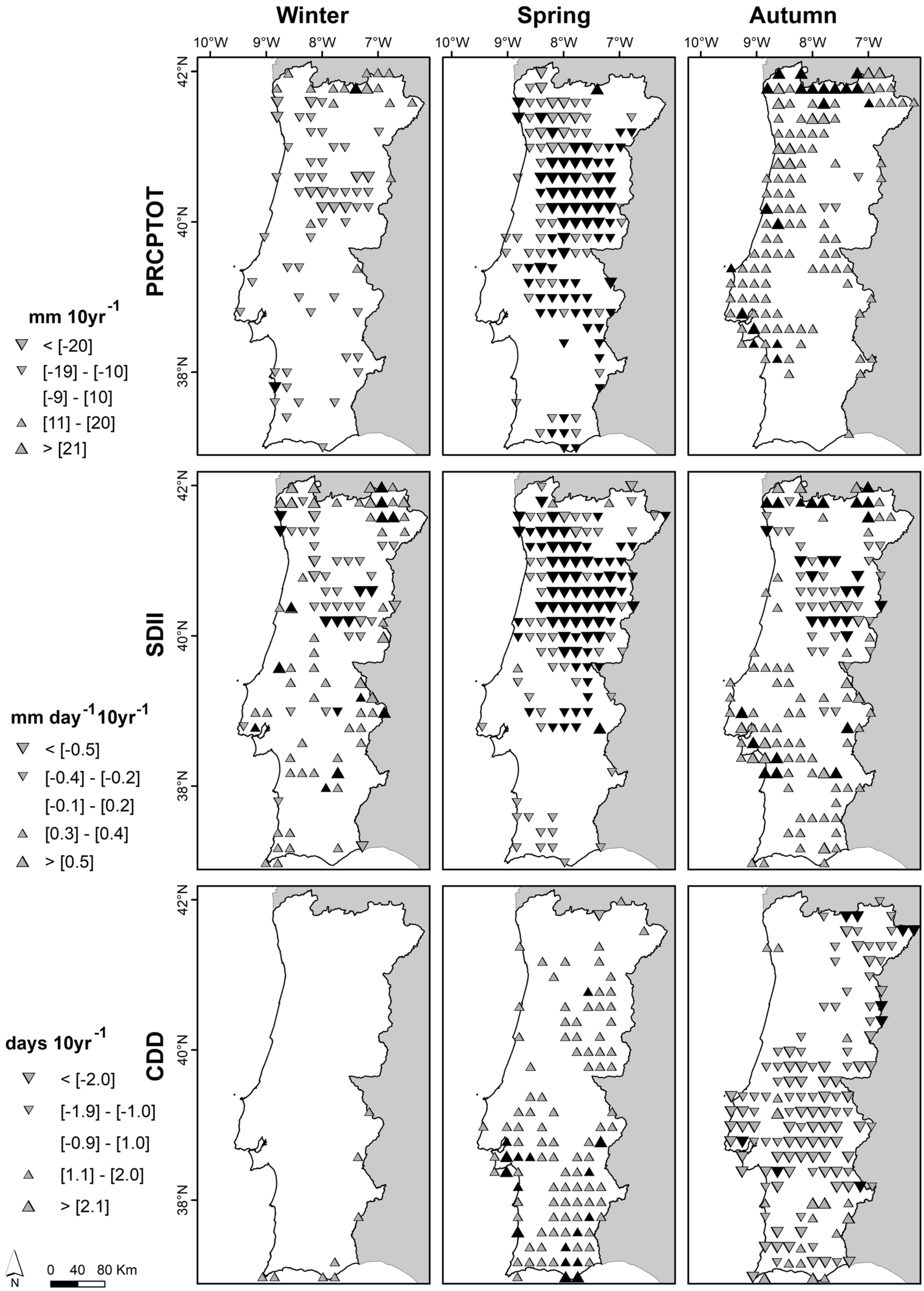


**Fig. 3** Seasonal trends (winter, spring and autumn) of PRCPTOT, SDII, and CDD for the period from 1950 to 2003. Triangles represent the Sen's slope per decade. Upward and downward triangles indicate positive and negative trends, respectively. The size of the triangles indicates the magnitude of the trend as identified in the respective legend. Black triangles correspond to statistically significant trends at 5% significance level (Z Kendall's coefficient)

(PT02) was bilinearly interpolated to the EURO-CORDEX grid (coarser grid) and was used as a baseline for the point-by-point bias corrections in the training period of 1986–2005. The future projections of the different indices are presented as equally weighted ensemble means.

## 3 Results

Figure 2 shows the annual trends in precipitation indices over mainland Portugal, from 1950 to 2003. A decreasing trend of annual precipitation over northern and central Portugal is apparent, which is also consistently suggested by other precipitation indices, including R×1day, R×5day, SDII, R20 and R95PTOT. The maximum number of consecutive wet days (RR ≥ 1 mm, CWD) increases in the north-central part of the country, but these trends are statistically significant at only 4% of the gridboxes. In the south, CWD decreases, but these changes are statistically significant at only 7% of the gridboxes. CDD shows statistically significant decreasing trends at 3% of gridboxes. Overall, these results hint at a drying trend over the period of 1950–2003, mainly in central Portugal.

An overview of the seasonal trends is given in Fig. 3, S2 and S3. In general, increasing trends are detected in autumn, while negative trends are estimated for spring. In spring, PRCPTOT shows drying (negative) trends, from − 30 to − 1 mm decade$^{-1}$, which are significant for more than 29% of the gridboxes. CDD shows an increasing trend in spring (< 2 days decade$^{-1}$, on average) in central and southern Portugal, but statistically significant at only 7% of the gridboxes. Conversely, CWD tends to decrease, being statistically significant at 16% of the gridboxes.

In autumn, there is a slight increase in total precipitation (PRCPTOT), along the coastal strip and in the north of the country, though statistically significant at only 7% of the gridboxes. The increasing trends vary between 1 mm decade$^{-1}$ and 40 mm decade$^{-1}$. CDD reveals a decreasing trend of up to −3 days decade$^{-1}$, but it is statistically significant at only 4% of the gridboxes (Fig. 3). CWD reveals a slight wetting trend, mainly in northern and central Portugal, but often not statistically significant (only in 9% of gridboxes). The contribution from very wet days (R95PTOT) hints at a downward trend (statistically significant at only 9% of the gridboxes), mostly in autumn over central Portugal (Fig. S3).

In winter, in general, the observed trends are not statistically significant, though weak drying trends prevail over central Portugal (Fig. 3). Similar considerations can be made for SDII (Fig. 3), R×1day, R×5day, R20 (Fig. S2). The decrease of CWD in winter is particularly clear in the south, being statistically significant at 26% of the gridboxes (Fig. S3).

The EPSI seasonal trends systematize the results presented above (Fig. 4). In winter, there are no spatially consistent trends. The increasing trends are detected in autumn, along a strip in the north and in the Lisbon region, while negative trends are estimated for spring, mainly in the central region.

The inter-annual variability of the selected precipitation indices is presented in Fig. S4, averaged over mainland Portugal and for the period of 1950–2003. The PRCPTOT index shows a strong inter-annual variability, with a sequence of very rainy and very dry winters. Fig. S4 shows that the highest values of SDII are not always related to the highest values of PRCPTOT. According to the Pettitt test, it is possible

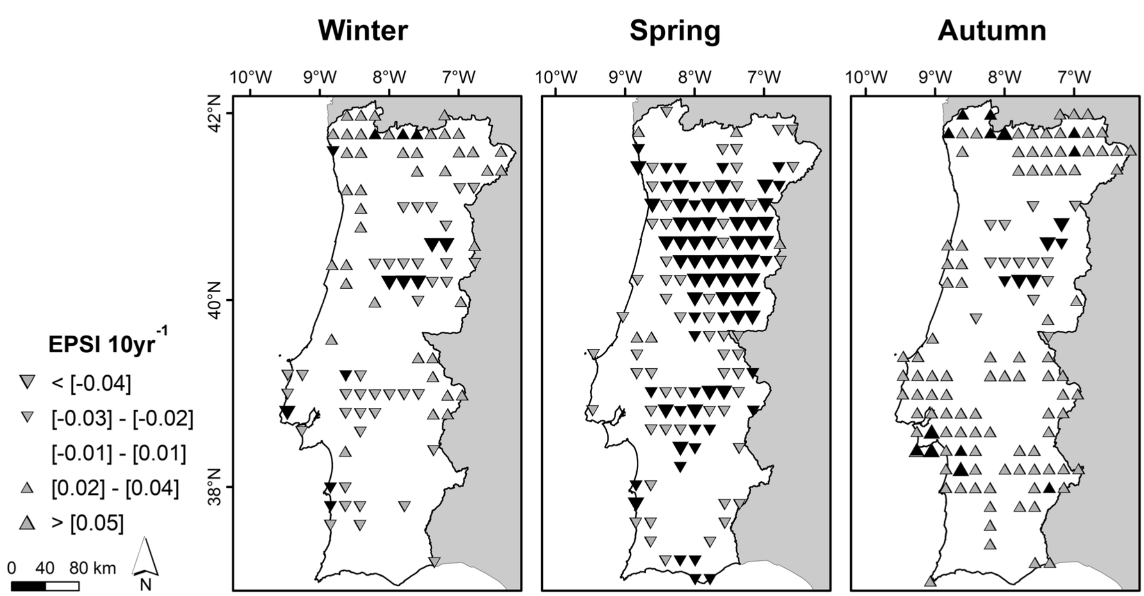


**Fig. 4** Seasonal trends of EPSI (adimensional) in the period from 1950 to 2003. Triangles represent the Sen's slope per decade. Upward and downward triangles indicate positive and negative trends, respectively. The size of the triangles indicates the magnitude of the trend as identified in the respective legend. Black triangles correspond to statistically significant trends at 5% significance level (Z Kendall's coefficient)

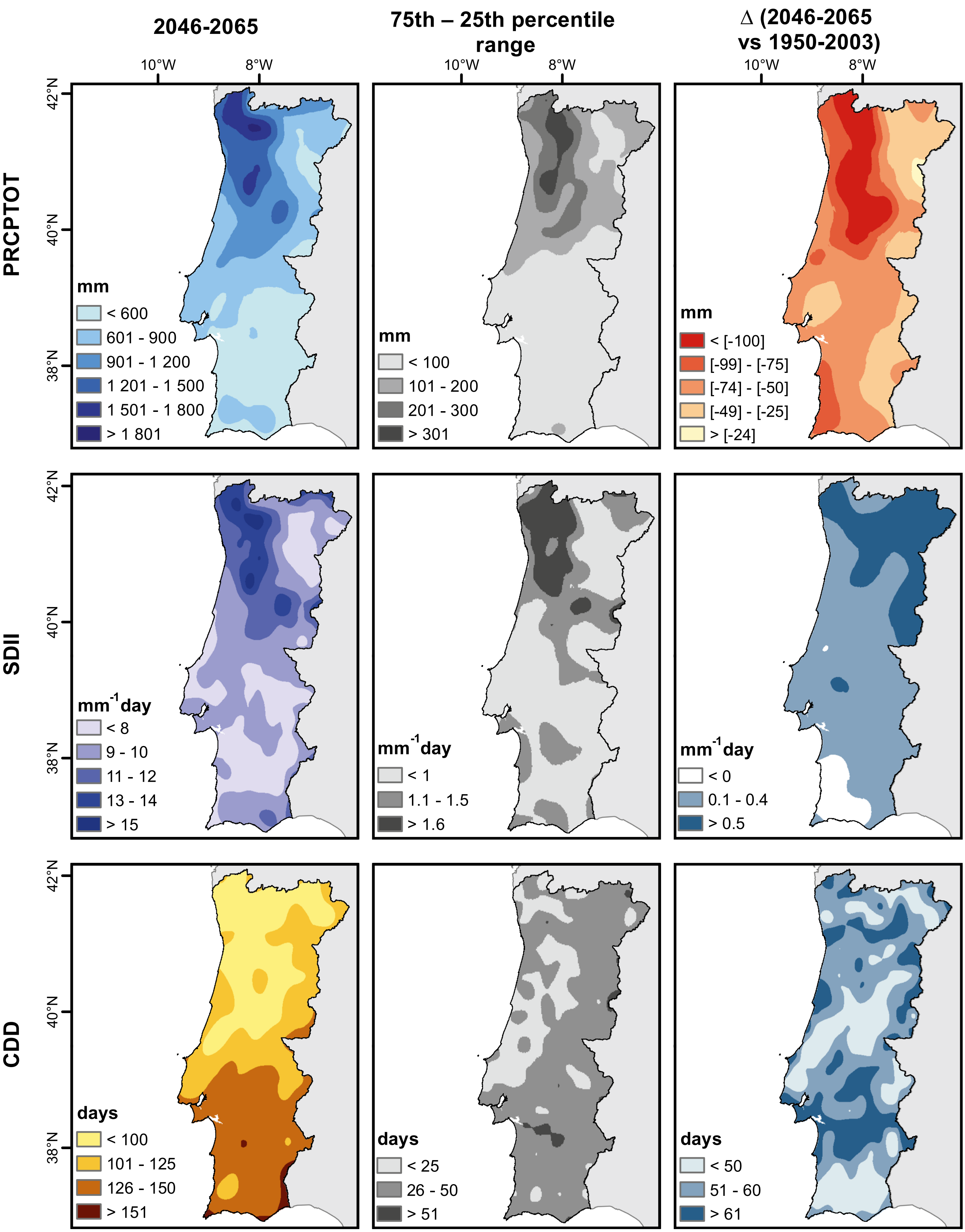


**Fig. 5** *Left panel*: ensemble mean precipitation indices for the period of 2046–2065 (PRCPTOT, SDII and CDD). *Middle panel*: corresponding 75–25th percentile range. *Right panel*: corresponding climate change signals (seven-member ensemble mean for 2046–2065 minus 1950–2003)

to identify statistically significant change-points (at 5% significance level) in the spring of 1969 for R×1day, R×5day, SDII and R20. The maximum number of consecutive dry days (CDD) index also highlights strong inter-annual variability. The highest values are recorded in autumn and spring. The R95PTOT reveals that more extreme precipitation tends to occur in autumn than in winter (Fig. S4).

The NAO index, between 1950 and 2003, reveals a statistically significant positive trend in spring and winter. Conversely, the EA index shows a negative trend in winter and in spring, but statistically significant only in the latter. No statistically significant trend is detected in autumn (Fig. S5). The ensemble mean precipitation indices for 2046–2065, the respective 75–25th percentile ranges and the differences between 2046–2065 and 1950–2003 are shown in Fig. 5, S6 and S7. The individual model projections are not detailed for the sake of succinctness, but their 75–25th percentile ranges are a measure of the inter-model uncertainty. The northwest-southeast precipitation gradient and the orography footprint are also observed in the model ensemble. Figure 5 shows a reduction in mean precipitation (PRCPTOT), between approximately 30 and 110 mm, but accompanied by an increase in the other indices (SDII, CDD, R×1day, R×5day, CWD, and R95PTOT). Increases in the mean maximum number of consecutive wet days, from 10 days in the northwestern coast to 5 days in the northeast are projected for the future. R×5day and R×1day show significant increases over northern Portugal. In fact, the highest consecutive 5-day precipitation total (R×5day) is expected to increase, on average, by at least 126 mm in the northern mountains (Fig. S6). The projected significant increase in CDD is particularly clear, as the maximum number of the consecutive dry spells are predicted to increase by more than 55 days in the inner-south and inner Douro Valley, and by more than 45 days in the rest of the country (Fig. 5). The contribution of extreme precipitation to total precipitation (R95PTOT) is also expected to increase, mainly in southern Portugal (Fig. S7).

For current climates, the dominant classes of EPSI (Santos et al. 2017) are "high" or "very high" in more than 60% of the municipalities (Fig. 6 and Table S2). The highest

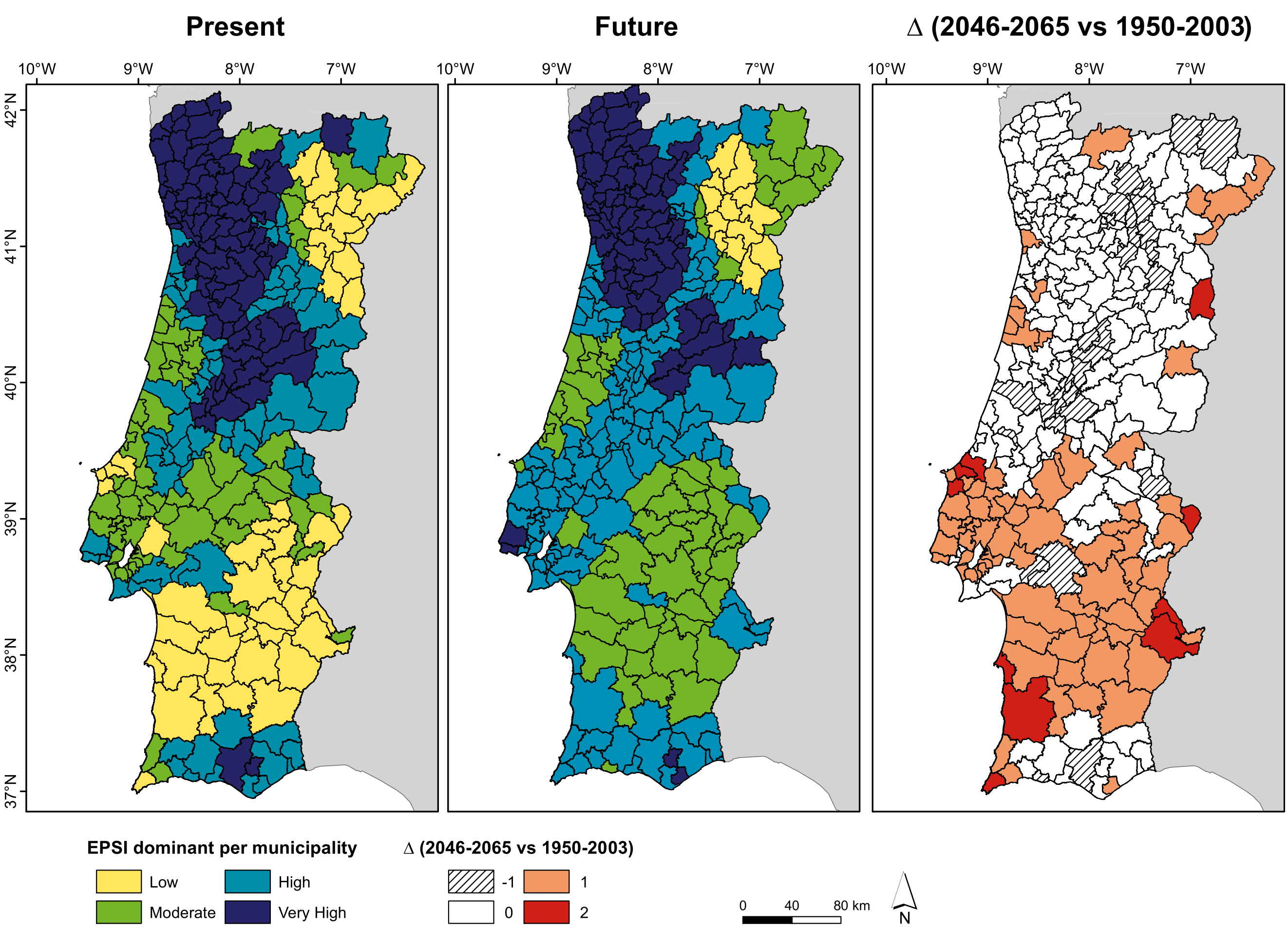


**Fig. 6** Present (1950–2003), future (2046–2065) and difference between 2046–2065 and 1950–2003 of the dominant extreme precipitation susceptibility index (EPSI) in mainland Portugal, aggregated by municipality. The corresponding climate change signal (seven-member ensemble mean for 2046–2065 minus 1950–2003) is measured by the difference in the class rank (e.g., a change from "Low" to "Moderate" corresponds to + 1)

susceptibility areas are in the mountains of northern and central Portugal, as well as in the southern coastal area (Santos et al. 2017). On the other hand, the lower susceptibility are in the northeast, in inner-south, and along the central-western coastal municipalities (Santos et al. 2017). The EPSI future projections for 2046–2065 reveal an increase in susceptibility for 29% of the municipalities. About 60% of the municipalities maintain the dominant susceptibility class, but 74% of them are classified with "high" or "very high" extreme precipitation susceptibility. The increase in susceptibility is more pronounced in the region of Lisbon and in the inner-south (Fig. 6). The susceptibility is also expected to increase for almost all municipalities in the Lisbon metropolitan area (currently, with more than 2.8 million people, ~27% of the total national population).

Figure 7 shows the CDD (maximum number of consecutive dry days) aggregated by municipality in the present and future. An increase of CDD values throughout the country is also apparent in the future period (2046–2065), particularly in the southern municipalities.

The 278 municipalities were spatially grouped using the Ward's agglomerative hierarchical clustering method and based on both EPSI and CDD. This clustering divided the country into three regions characterized by different values of EPSI and CDD. Cluster 1 shows a near-average EPSI and a high CDD and mainly comprises the Lisbon metropolitan area and most of southern Portugal. Cluster 2, mostly composed by the municipalities of the northern and central coast, typically presents high EPSI and low CDD values. Finally, cluster 3, mainly covering the northeastern municipalities, features low EPSI and CDD values. In the future, a decrease in the coverage of cluster 3 and increases in clusters 1 and 2 are projected (Fig. 8). The EPSI and CDD averages by NUTS-3 (Nomenclature of Territorial Units for Statistics) regions confirm the spatial heterogeneity of the country: NUTS-3 regions located in north-western Portugal tend to present high EPSI values, while those in the south tend to depict high CDD values. The projected increases of CDD in the Trás-os-Montes (northeast) and in central regions are also noteworthy (Fig. S8).

## 4 Discussion and conclusions

A number of selected precipitation indices, in mainland Portugal over the period of 1950–2003, were herein studied at annual and seasonal scales. Predominantly drying trends in

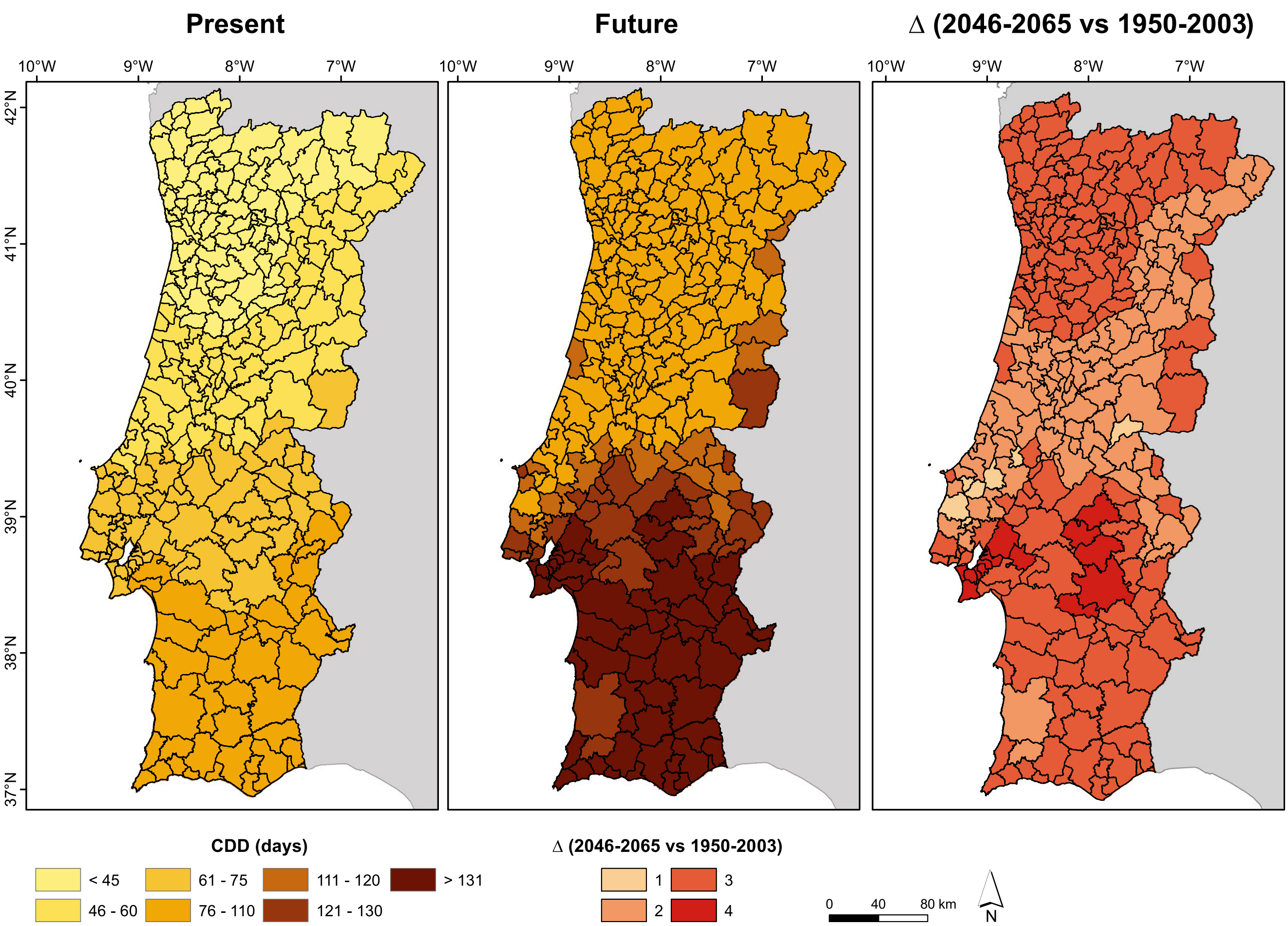


**Fig. 7** As in Fig. 6, but for CDD

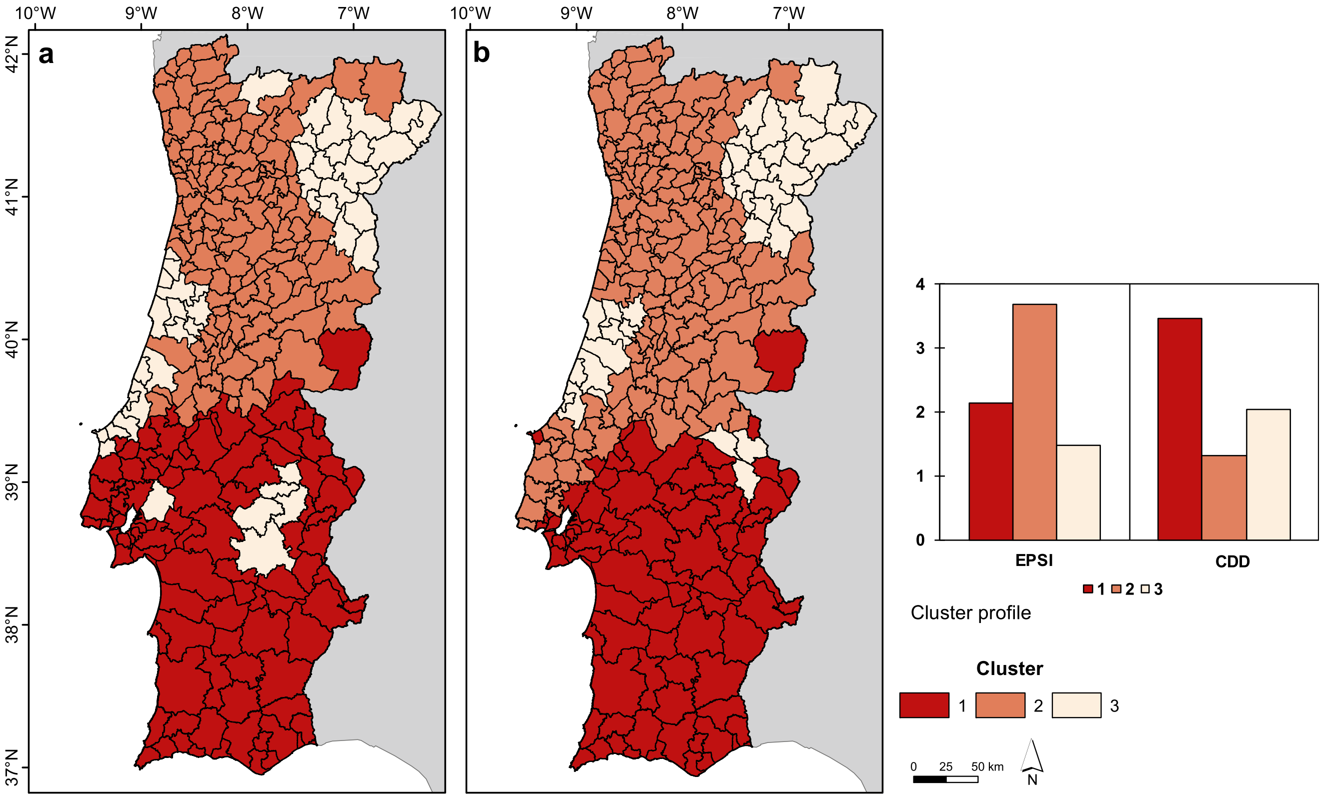


**Fig. 8** EPSI-CDD (labeled as 1,2, and 3) clusters in mainland Portugal for **a** 1950–2003 and **b** 2046–2065. The respective cluster profiles (EPSI and CDD averages for each cluster) are also outlined on the left bar charts

the precipitation indices were identified, mainly in central Portugal. This is consistent with the results reported by Lima et al. (2015), though the majority of stations did not show statistically significant changes in the period of 1941–2007. In spring, statistically significant drying trends were found, mainly in northern and central Portugal, while weak wetting trends were detected in autumn, but not significant at 5% level. Similar outcomes were obtained in previous studies (e.g., Lima et al. 2013; Espírito Santo et al. 2014). The EPSI trends also confirm the previous results, i.e., a decrease of extreme precipitation occurrences in spring over central Portugal and a slight increase in autumn over northern Portugal and nearby Lisbon. Decreased precipitation in winter and spring over Southwestern Europe and Northwestern Africa is commonly associated with the predominance of the positive phase of the NAO over the last four decades (e.g., Goodess and Jones 2002; Sáez de Cámara et al. 2015; Santos et al. 2016). The East Atlantic pattern (EA) is also a prominent large-scale pattern within the Euro-Atlantic sector that significantly controls the precipitation and air temperature patterns over Portugal (Santos et al. 2007; Santos et al. 2013). Santos et al. (2018) showed that most floods in northern Portugal over the period of 1865–2014 occur during the positive phase of EA. Overall, the results obtained in the present study are in clear agreement with previous studies, by showing that the decrease in spring precipitation is associated with a strengthening of the positive phase of NAO and of the negative phase of the EA pattern. Although the results are not so clear as for precipitation, the NAO negative phase tends to be favorable to the occurrence of floods in Portugal (Silva et al. 2012; Santos et al. 2018).

Climate change projections for 2046–2065 reveal a decrease in PRCPTOT, mainly over northwestern Portugal. The contribution of extreme precipitation to total precipitation (R95PTOT) is expected to increase, particularly in southern Portugal. The maximum number of consecutive dry days (CDD) is also projected to increase significantly throughout Portugal. The remaining precipitation indices tend to increase in the 2046–2065 period. These findings are also in general agreement with previous studies (e.g., Costa et al. 2012; Melo-Gonçalves et al. 2016; Soares et al. 2017). EPSI is projected to increase in 29% of the Portuguese municipalities and 74% of them will thus present “high” or “very high” extreme precipitation susceptibility, including in almost all municipalities in the Lisbon metropolitan area. CDD will also increase, particularly in southern Portugal, with potential consequences on, e.g., agriculture, water management, and hydroelectric power production. The EPSI and CDD summarize the characteristics of precipitation and the combination of this information by municipalities can be of foremost significance to civil protection and municipal services. Despite the overall decrease in precipitation, the increase in the occurrence of extreme events accentuates the vulnerability of most municipalities in the future, with obvious detrimental implications in various socio-economic sectors, such as agriculture, water management, forests, and, eventually, disasters. The information aggregated by municipalities showed that the northern region is more susceptible to extreme precipitation events, while the south of the country is more susceptible to long drought events. In forthcoming research, the scale of the analysis will be reduced through the application of hydrological models to specific river basins and the integration of EPSI with other natural triggers in order to mitigate natural hazard risks in Portugal under changing climate.

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