National Roadmap for Adaptation 2100

Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

REPORT

WP4 – Sectoral Impacts Modelling

Droughts

2nd Progress Report

National Roadmap for Adaptation 2100

Portuguese Territorial Climate Change Vulnerability Assessment for XXI Century

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Authors: Pedro Matos Soares (coord.), Daniela Lima, João Careto, Ana Russo.

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List of Acronyms

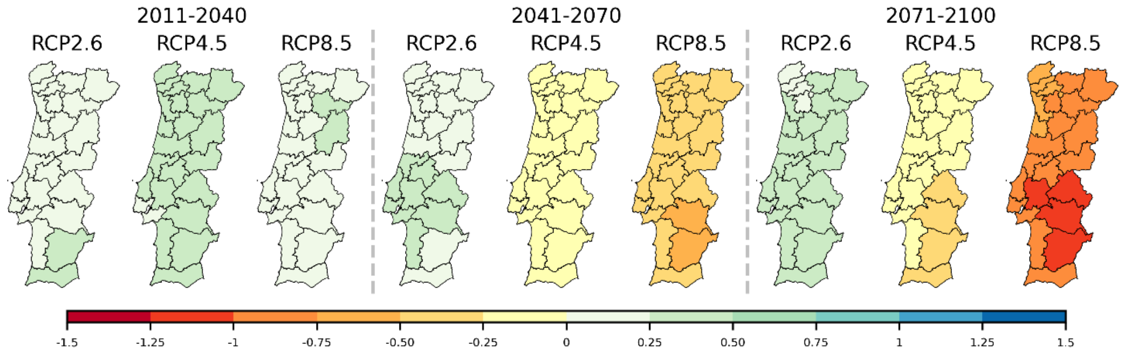
PDSI	Palmer Drought Severity Index
SPI	Standardized Precipitation Index
SPEI	Standardized Precipitation Evapotranspiration Index
IP	Iberian Peninsula
RCP	Representative Concentration Pathway
EURO-CORDEX	European branch of the Coordinated Regional Climate Downscaling Experiment
RCM	Regional Climate Model
CMIP5	Coupled Model Intercomparison Project – Phase 5
PET	Potential Evapotranspiration

Summary

Amongst all natural hazards, droughts are one of the costliest, with cross-sectorial concurrent negative impacts, encompassing health, agriculture, vegetation activity/productivity, water resources, forest fires and energy production. Droughts manifest globally with either a rapid onset or a slow development, spreading across large areas, and with impacts that can linger long after the end of the event. As a result of warming and precipitation deficits and the increasing shortage of water resources, droughts have become one of the main drivers of desertification, land degradation and food insecurity, with direct impacts on ecosystems and society, especially in fragile communities. Iberia has been identified for decades as a climate change hotspot, especially due to its vulnerability to temperature extremes, precipitation reductions, and consequent associated droughts. Over Iberia, the occurrence of droughts varies in intensity and severity, making its assessment under present and future conditions an important tool for adaptation measures.

We present a comprehensive analysis of the different plausible evolutions of droughts throughout the 21st century over Iberia on a monthly basis, featuring three different emission scenarios (RCP2.6, RCP4.5, RCP8.5). A multi-variable, multi-model EURO-CORDEX weighted ensemble (explain in detail in WP2 Report) is used to assess future drought conditions using the SPI (Standardized Precipitation Index) and SPEI (Standardized Precipitation Evapotranspiration Index) at 1-, 3-, 6-, 12- and 24-month timescales. All indices were computed using, the 1971 to 2100 period as reference, i.e., the historical period from 1971 to 2000 was merged with the 2011 to 2100 from each RCP scenario.

The results clearly show that Iberia is highly vulnerable to climate change, indicating a significant increase in the intensity and severity of drought occurrences, even for the low-end RCP2.6 scenario. For the RCP4.5 and RCP8.5 scenarios, the increases are more pronounced and enhanced throughout the 21st century, from 3 up to 12 more severe droughts for the shorter timescales with increases in mean duration above 30 months for the longer accumulation periods. The use of all the RCPs data pooled together with a multi-variable weighted ensemble approach allows not only a more accurate and robust projection of future droughts but also ensures comparability among the projections from the three RCP scenarios.



Annual average of SPEI-12 over mainland Portugal for the future periods considering different GHG emission scenarios.

1. Introduction

Iberia has been identified for decades as a climate change hotspot (Lionello 2012; Diffenbaugh et al. 2012; Turco et al. 2015; Russo et al. 2019; Cos et al. 2022) especially due to its vulnerability to temperature extremes (Cardoso et al. 2019), precipitation reductions (Argueso et al. 2012; Soares et al. 2017a), the associated droughts (Hoerling et al. 2012) and the related impacts. In Southern Europe, and in particular in Iberia, droughts occur often and with varied intensities and severities (Páscoa et al. 2020; Liberato et al. 2021), having sectoral, e.g. agriculture, energy production (Peña-Gallardo et al. 2019; Ribeiro et al. 2019a, 2019b; Després and Adamovic 2020), environmental, e.g. vegetation activity/productivity, water resources, forest fires (López-Moreno et al. 2007; Gouveia et al. 2012; Bastos et al. 2014; Bifulco et al. 2014; Kurz-Besson et al. 2016; Russo et al. 2017) and human negative impacts (Salvador et al. 2019, 2020a, 2020b).

In general, drought conditions are defined by the balance between water availability, demand, and management (Vicente-Serrano et al. 2020). In this sense, drought is greatly influenced by atmospheric dynamics and land–atmosphere feedbacks (Sousa et al. 2011; Vicente-Serrano et al. 2015; Geirinhas et al. 2021). The presence of circulation systems, like atmospheric blocking systems or ridges, modulates the storm tracks over the North Atlantic and the associated moisture fluxes towards the continent on synoptic time scales, therefore exerting a strong influence on precipitation anomalies and consequently on droughts (Stojanovic et al. 2018; García-Herrera et al. 2019). Furthermore, drought also depends on atmospheric evaporative demand, which may further reinforce drought severity when an increased evaporative demand is settled (Geirinhas et al. 2021). To consider the different feedbacks involved in the drought onset and duration, different approaches to depict drought occurrence have been developed. One of the most common is to identify meteorological droughts with the use of proxy indices, namely the Palmer Drought Severity Index (PDSI, Palmer 1965), the Standardized Precipitation Index (SPI, McKee et al. 1993), or the Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano et al. 2010). These indices allow for an indirect assessment of drought through a simplified calculation of the main feedbacks, the latter two with multi-scalar characteristics. Despite the worldwide acceptance of SPI and its World Meteorological Organization recommendation to monitor droughts, SPEI has gained ground in the last years due to its capability for accounting the increase of atmospheric evaporative demand derived from temperature increases, in result of anthropogenic greenhouse gas effect (García-Valdecasas Ojeda et al. 2021). In fact, SPEI accounts for temperature influence (Vicente-Serrano et al; 2010), which is particularly important during periods of precipitation deficits over water-limited regions (Knist et al. 2017; Careto et al. 2017; Soares et al. 2019; Tomas-Burguera et al. 2020).

Recently, Páscoa et al. (2020), taking advantage of the new high-resolution regular gridded dataset for Iberia (0.1° horizontal resolution), which includes precipitation and temperatures (Herrera et al. 2019), presented a high-resolution drought assessment focused on the Iberian Peninsula (IP) for present climate. This study used both SPEI and SPI for short-, medium- and long-timescales, for the 1971–2015 period. A clear drying trend in most of the IP was identified by both indices for most of the territory, whereas the mean drought intensity was found to decrease slightly. The drivers of this drying trend are both the decreased precipitation and the increased evapotranspiration. With Páscoa et al. (2020) more complex patterns of drought trends were identified, mainly due to the improved description of precipitation, but a climate change perspective was lacking. This caveat has been examined taking into consideration future projections of drought events at both global and regional scale (e.g Spinoni et al. 2018, 2020, 2021), assessing the impacts on different economic sectors, such as agriculture, water management, and electricity production (e.g Bento et al. 2021; Guerreiro et al. 2017; Després and Adamovic 2020). Regarding the understanding of future Iberian droughts, the few previous studies based on regional climate models display some limitations. Guerreiro et al. (2017) only looks upon projections from one Representative Concentration Pathway (RCP) scenario, the RCP8.5 for mid-century (2041-2070) to analyse the flows of the international basins of Douro, Tagus, and Guadiana. García-Valdecasas Ojeda et al. (2021) relied on the EURO-CORDEX (European branch of the Coordinated Regional Climate Downscaling Experiment) multi-model ensemble under RCP8.5 to assess future drought conditions based on the calculation of SPEI at 3- and 12-month timescales. One of the major highlights from this work is related to the strong dependency of projections of drought characteristics on the period considered to calibrate the SPEI, particularly for larger timescales. Additionally, they reported that differences were larger for the near future than for the end-of-century. This work has several shortcomings, namely the use of a multi-model average with all members having the same weight in the ensemble, does not include the complementary RCPs, which are gaining plausibility, and does not use shorter timescales. The study from Spinoni et al. (2017) tries to overcome some of the previous limitations, by using regional climate model (RCM) runs, also from the EURO-CORDEX initiative, after bias correction. Spinoni et al. (2017) assessed future drought conditions in Europe through SPI and SPEI, by using the Hargreaves–Samani equation, and also the reconnaissance drought indicator (RDI) at 3- and 12-month scales. For each simulation, the frequency and severity of drought and extreme drought events was assessed for 1981–2010, 2041–2070, and 2071–2100, for both the RCP4.5 and RCP8.5. The authors highlight that although the bias correction brings significant improvements, some underestimation of extreme droughts is still present even when using the bias-adjusted EURO-CORDEX simulations, linked to the length of the considered period. Specifically for the Iberian Peninsula, Moemken et al. 2022 show an increase of drought conditions for the future climate. The authors also apply a bias correction methodology to EURO-CORDEX simulations and afterwards use standardized indexes for precipitation deficit, applying the results to global warming levels under the RCP 8.5 scenario.

Although these latter studies also use multi-model ensembles of RCMs, in particular from the EURO-CORDEX, they do not feature the model quality to represent drought over Iberia. Moreover, these investigations do not include the three main RCPs from the Coupled Model Intercomparison Project – Phase 5 (CMIP5), which undermines the possibility of fully characterising the benefits of greenhouse gas emissions mitigation, more aligned with the Paris agreement and the new national determined commitments, such as the ones of European Union and United States of America, and crucial for the design of efficient and informed adaptation measures for different scenarios. Thus, is still missing a thorough drought assessment for Iberia, at high resolution, considering a weighted multi-model ensemble and a multi-scenario for greenhouse gas emissions, from near- to end-of-century.

In the current study, the evolution of droughts over Iberia is revisited, based on a high-quality EURO-CORDEX weighted multi-model ensemble, including, for the first time, the three RCPs from CMIP5: RCP2.6, RCP4.5 and RCP8.5 (van Vuren et al. 2011) and based on monthly drought indices. Firstly, a weighted multi-model ensemble for drought assessment is built where the weighting process relies on the individual model quality to represent both temperature and precipitation, the key variables for computing the evaporative demand (P-PET) and thus SPI and SPEI indices. The temporal scales considered range from 1 month to 24 months. Secondly, the future drought anomalies, with respect to present climate, are analysed for three future climate periods (2011-2040; 2041-2070 and 2071-2100) in agreement with the three RCPs scenarios. Incorporated on the National Roadmap for Adaptation 2100 – Assessment of the Portuguese territory's vulnerability to climate change in the 21st century (RNA 2100) project, which aims to support multi-sectorial public policy exercises of adaptation to climate change, a special focus is given to the future drought properties in response to the different emission scenarios. In this way, a clear avenue for the adaptation needs, linked with meteorological droughts, can be drawn for Iberia.

2. Data and Methods

2.1. EURO-CORDEX

The World Climate Research Programme supported a COordinated Regional Downscaling EXperiment (CORDEX) with the main goal of developing a coordinated ensemble of high-resolution RCMs projections throughout the 21st century for all regions of the world, at user relevant scales, to support climate change impact and adaptation research (Giorgi et al. 2009; Gutowski et al. 2016). EURO-CORDEX (Jacob et al. 2014, 2020) is a branch from the international CORDEX framework, consisting of ensembles at 0.44º, 0.22º, and 0.11º horizontal resolutions, covering a European domain.

These simulations span a common period from 1971-2100, where RCMs downscale the information from the Intergovernmental Panel on Climate Change - CMIP5 Global Circulation Models. From 2006 onwards the simulations consider the RCP of 2.6, 4.5 and 8.5 W/m^2 (van Vuren et al. 2011) as future greenhouse gas emissions, which however are not considered evenly by all modelling groups. These three scenarios are used in the current study to assess the difference in future drought projections from a strong mitigation scenario to a scenario without mitigation.

The used EURO-CORDEX variables were retrieved through the Earth System Grid Federation (ESGF) data portal and include daily total precipitation, maximum and minimum 2-m daily temperature. In total 13 EURO-CORDEX ensemble members were considered, covering all the required experiments. Table 2.1 summarizes the regional climate information used in this work.

Table 2.1 EURO-CORDEX Regional models driven by the CMIP5 GCMs. The last column denotes the weights given to each individual model.

CMIP5 GCM	Variant	RCM	Reference	Weights
CNRM-CERFACS-	r1i1p1	CNRM-ALADIN63	Daniel et al. (2019)	2.43E-03
CNRM-CM5	r1i1p1	KNMI-RACMO22E	van Meijgaard et al. (2008)	4.92E-03
ICHEC-EC-EARTH	r12i1p1	CLMcom-CCLM4-8-17	Keuler et al. (2016)	2.42E-01
	r3i1pi	DMI-HIRHAM5	Christensen et al. (2007)	1.42E-02
	r12i1p1	KNMI-RACMO22E	van Meijgaard et al. (2008)	2.67E-01
	r12i1p1	SMHI-RCA4	Samuelsson et al. (2011)	1.95E-02
MOHC-HadGEM2-ES	r1i1p1	DMI-HIRHAM5	Christensen et al. (2007)	3.16E-02
	r1i1p1	KNMI-RACMO22E	van Meijgaard et al. (2008)	1.43E-01
	r1i1p1	SMHI-RCA4	Samuelsson et al. (2011)	2.55E-02
MPI-ESM-LR	r1i1p1	MPI-REMO2009	Jacob et al. (2012)	2.61E-02
	r1i1p1	SMHI-RCA4	Samuelsson et al. (2011)	1.29E-02
NCC-NorESM1-M	r1i1p1	GERICS-REMO2015	Remedio et al. (2019)	1.93E-01
	r1i1p1	SMHI-RCA4	Samuelsson et al. (2011)	1.84E-02

The EURO-CORDEX simulations were extensively evaluated for present climate, showing substantial improvements for the main climate variables in simulating the variability of the European climate in space and time (Vautard et al. 2013, Kotlarski et al. 2014, Katragkou et al. 2015, Prein et al. 2015; Remedio et al. 2019). Over Portugal, Soares et al. (2017a) and Cardoso et al. (2019) assessed the ability of multi-model EURO-CORDEX ensembles in reproducing precipitation and temperature patterns and its variability, revealing a good agreement with observations and substantial gains when compared with previous RCM projects (PRUDENCE and ENSEMBLES; Soares et al. 2012). More recently, Herrera et al. (2020) performed a similar evaluation over the Iberian Peninsula, showing a good spatial agreement among EURO-CORDEX RCMs and observations. The added value of using such high-resolution simulations was quantified by Soares et al. (2018) for the first time over the European domain, reporting significant added value in the description of precipitation patterns, especially for extremes. Recently, the added value for temperature over Europe (Cardoso and Soares 2022), and for both climate variables over Iberian Peninsula (Careto et al. 2022a, 2022b), was assessed. Finally, EURO-CORDEX simulations were also able to reproduce the onshore (Moemken et al. 2018; Nogueira et al. 2019; Vautard et al. 2021) and offshore near-surface wind speed (Soares et al. 2017b).

2.2. Drought assessment

Due to the intricate characteristics of drought events and their relevant impacts to the environment and society, the use of drought indicators has become more frequent over the recent years (e.g Vicente-Serrano et al. 2010; Begueria et al. 2014; Spinoni et al. 2017; Russo et al. 2019). Two of the most commonly used multi-time-scale indices are SPI (McKee et al. 1993) and SPEI (Vicente-Serrano et al. 2010; Beguería et al. 2014). They both allow for different accumulation periods, which permits the assessment of different drought types and their different impacts (Vicente-Serrano et al. 2013; Russo et al. 2019; Ribeiro et al. 2019a, 2019b; Bento et al. 2021). SPEI and SPI fundamentally differ on the fact that the computation of SPI only relies on precipitation (Hayes et al. 2011), whereas SPEI computes a simplified water balance between precipitation and potential evapotranspiration (PET) (Vicente-Serrano et al. 2010, Beguería et al. 2014). In semi-arid regions, such as the Iberian Peninsula, and in a climate change context, the importance of temperature is seen as paramount (Beguería et al. 2014), pushing forward the increasing use of SPEI, as we propose in the current study.

In order to compute SPEI, the PET needs to be determined. Yet, there are numerous formulations for PET. One of the most widely used is the FAO-56 Penman-Monteith formula (Allen et al. 1998) tailored for non-stressed grass cover. A drawback from this approach is the need for multiple variables, some of them not readily available. Thus, a modified version of the Hargreaves formulation (MHg) is considered here (Droogers and Allen 2002) for its calculation. The MHg is similar to the original Hargreaves formulation, but includes precipitation, which is readily available in most modelling and observational datasets and may serve as a proxy for cloud cover and humidity. Here, a daily version of this formula is implemented (Farmer et al. 2011):

$$PET = 0.0019 * 0.408 * RA * (Tavg + 21.0584)(TD - 0.0874 * P)^{0.6278} \quad (1)$$

where RA is the extra-terrestrial radiation in MJ/m2, TD is the daily thermic amplitude in oC, Tavg is the daily mean temperature also in oC obtained from the average between the daily maximum and minimum temperature, and P is the precipitation in mm/day. In this case, the RA is obtained empirically (Kalogirou 2014). To do so, first the declination can be obtained by using the Cooper law:

$$\delta \ = \ 23.45 * sin((360/365) * (N + 284)) \quad (2)$$

where N corresponds to a certain day of the year, i.e., 1st January is day 1 and 31st December is day 365 or 366 depending on if it is a leap year. To compute the RA, the sunset hour angle is also a requirement and is given by:

$$\omega \ = \ cos - 1(-tan(\phi) * tan(\delta)) \quad (3)$$

where ϕ is the latitude and δ the declination obtained from the previous step. The RA in W/m^2 is then computed with equation 2.79 from Kalogirou (2014):

$$RA = ((24 * 3600 * Gsc)/\pi) * S * (cos(\phi) * cos(\delta) * sin(\omega) + \omega * sin(\phi) * sin(\delta)) \quad (4)$$

where Gsc is the solar constant corresponding to 1367 W/m^2 and the term S is the inverse distance earth-sun, given by:

$$S = 1 + 0.033 * cos(360 * N/365) \quad (5)$$

All angles were converted into radians, prior to each iteration.

2.3. Reference period for drought assessment

The usage of a standard reference period is common when computing both SPI and SPEI (e.g, Vicente-Serrano et al. 2010; Begueria et al. 2014), which is particularly useful for projections throughout the 21st century. However, due to the larger expected climate signal for the future, particularly for temperature (IPCC, 2021), the probability functions could fail in simulating the lower tail of the accumulated distributions. Thus, to avoid this drawback, the method used in Spinoni et al. (2018) with a small evolution is followed here, and the full period of data is considered to address drought future changes. In this way, the data is divided into two periods: 1) 1971-2000, which corresponds to the historical baseline (30-year); and 2) the full span from EURO-CORDEX (1971-2100). For the latter the drought indices are computed by pooling together the 300 years of data encompassing the periods from 1971-2000 together with each 2011-2100 period from the three RCP scenarios. This approach differs from the one proposed by Spinoni et al. (2018), and yet can only be used to assess the changes between future and historical conditions. It is important to highlight the difference between the historical reference period computed with only 30 years against the full 300 years. Therefore, any comparison of the historical periods needs to be carefully addressed. Since SPI and SPEI are standardised indices, both have a zero mean over the full span at which they are computed. However, this is not the case for the 1971-2000 period taken from the 300-year indices. In this case, the reference (1971-2000) tends to be more humid, leading to a reduced number of drought events as similar as reported by Spinoni et al. (2018). Moreover, larger differences at the end-of-century compared to the other periods could result in a slight underestimation of future events (Spinoni et al. 2018). In this sense, the 300-year SPI and SPEI are useful for assessing changes in drought characteristics for the 21st century, enhancing the comparability between RCPs, while the historical 30-year period is useful to evaluate present drought conditions as perceived by the EURO-CORDEX models.

2.4. Weighted multi-model ensemble based on temperature and precipitation

The building of weighted multi-model ensemble has shown to improve the quality of climate simulations, constraining the uncertainty, and obtaining more reliable climate projections (Christensen et al. 2010; Wenzel et al. 2016; Knutti et al. 2017; Sanderson et al. 2017; Lorenz et al. 2018; Brunner et al. 2019; Eyring et al. 2019; Nogueira et al., 2019). This is performed by weighting the individual models based on their performance in reproducing the variables of interest over a specific domain. Nonetheless, some studies have shown that different members of large multi-model ensembles have different performances in simulating given variables (Cardoso et al. 2019; Knutti et al. 2017; Nogueira et al. 2019; Sanderson et al. 2017; Soares et al. 2017a).

In the current study, two drought indices (SPI and SPEI) are used, where SPI relies on precipitation and SPEI on precipitation and temperature. In this way, a new approach to build a multi-model ensemble based on a multi-variable evaluation is followed to assess the future drought in Iberia. Here, we followed the methodology described in Lima et al. (2023) and in WP2 report (Climate Projections, Extremes, and Indices - Mainland Portugal) to build a weighted multi-variable multi-model ensemble based on precipitation and maximum and minimum temperature. This multi-variable approach is key to consistently assess both variables representation by the individual models, preserving the physical consistency among climate simulations. Additionally, this approach also fosters the use of the multi-model/multi-variable ensemble for impact modelling that often needs multi-variable information.

Firstly, an evaluation of the performance of the 13 EURO-CORDEX RCMs in simulating precipitation, maximum and minimum temperature was performed against the Iberia01 (IB-01) observational gridded dataset (Herrera et al. 2019) over Iberian Peninsula (Lima et al. 2023). This assessment was performed for the historical period (1971-2000), considering a set of different error metrics, from the systematic to the absolute errors, to distributions properties and extremes: mean bias, mean absolute error, root mean squared error, normalised standard deviation, spatial correlation, Willmott-D Score, Perkins skill score, and Yule-Kendall skewness. Based on this assessment, the weights for each model and for each variable were obtained considering the individual model performance in reproducing the observed climate (a detailed description on how the model weights is computed can be found in Lima et al. (2023)). To consider the multi-variable performance, a new weight for each model is computed where the precipitation weight contributes 50 %, and the maximum and minimum temperature both corresponds to 25% to the calculation of each model final weight (Table 2.1). The multi-model ensemble is then computed with those weights. Overall, the weighted multi-model ensemble has showed a good performance in representing the means and extremes of precipitation and maximum and minimum temperature when compared with IB-01 during the present climate over Portugal (similar results were found over Iberian Peninsula; Lima et al. 2023). This gives us confidence to use it in the characterisation of the future of climate extremes. Also, this new multi-variable approach enhances the consistency to the assessment of drought conditions based on SPI and SPEI.

2.5. Future drought assessment

To assess drought conditions throughout the 21st century and according to multiple emission scenarios, the mean values, the decadal frequency, and the mean duration of drought events are examined. These metrics were computed for periods of 30 years regarding the historical reference period 1971-2000, 2011-2040 corresponding to the near future, 2041-2070 to mid-century and 2071-2100 to the far future. For each individual model, the index mean value is useful to understand the trend across the different periods and is obtained by simply averaging each respective 30-year period. The decadal frequency is represented by the number of occurrences of a certain drought type per decade and, the mean duration of droughts is computed by dividing the total number of months in drought by the total number of events, for each drought class. Having the mean, frequency and duration for the individual models, the multi-model ensemble is built by considering the weights as introduced in the previous sub-section. Moreover, a boxplot of each projected change is built for intensity, the decadal frequency and mean event duration allowing a better assessment of the overall changes throughout the 21st century. Furthermore, for the drought projections a significance test is performed following the Welch t-test, where only differences with a p-value below 0.05 are considered significant. In addition, the uncertainty of the drought intensity, frequency and mean duration projections is also assessed. If the agreement of signal is poor among the individual model projections, then the uncertainty of the ensemble projections is higher. Conversely, if all models agree with the change signal, this indicates a reduced uncertainty.

Different types of droughts are examined: moderate drought for values below -0.5, severe drought for values below -1 and extreme drought for values below -1.5 (McKee et al. 1993). A drought event is determined when the SPI or SPEI index is below the threshold defined previously for at least one month. It is assumed that droughts evolve relatively slowly over time and for a specific event to be extreme, first it must also be severe and moderate. This assumption avoids cutting in half a single event considered to be moderate, which otherwise could lead to an overestimation in frequency and an underestimation in duration.

A flowchart to guide the readers through the methodology applied in this study is introduced in Figure 2.1, with the steps from the GCMs to the assessment of future drought conditions.

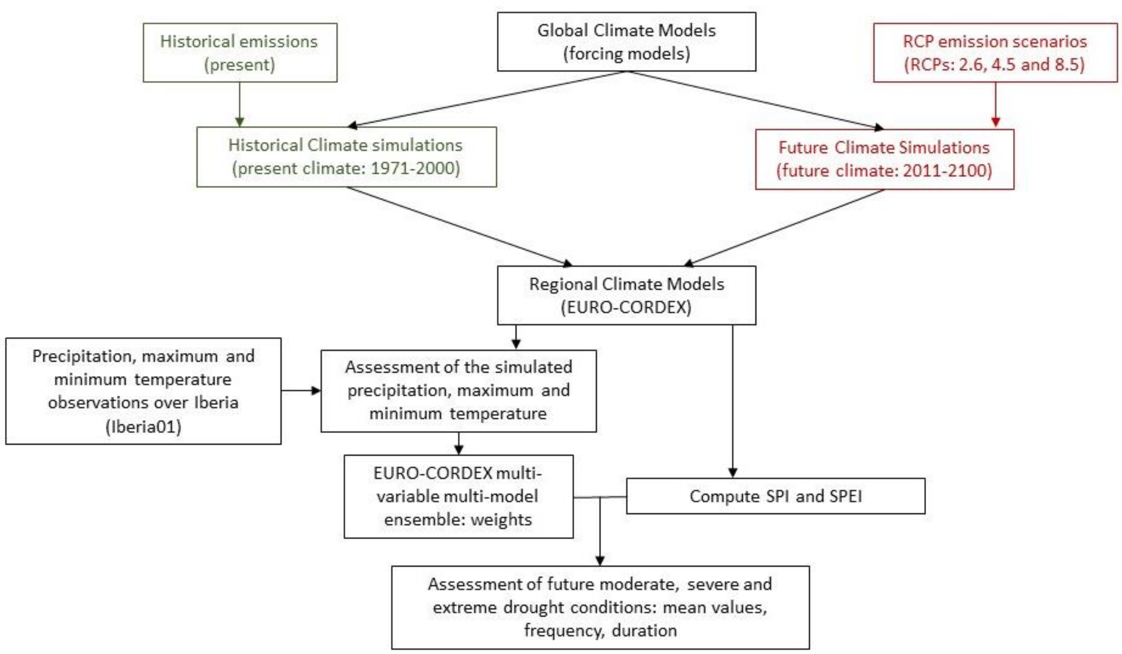


Figure 2.1 Flowchart of the data and methodology used in this study.

3. Results

3.1. Historical climate

An evaluation of the performance of the EURO-CORDEX multi-model ensemble is carried on against the Iberia01 observational dataset (Figure 3.1). Table 3.1a shows the results of the mean spatial bias for drought frequency, which is complemented by Figure 3.2a, which displays the distribution of those biases. These results feature the values for moderate, severe, and extreme drought. Overall, the smaller accumulation scales reveal higher differences against the observations, which is expected since the number of events at 1-month accumulation is higher (Figure 3.1a). Looking to the different drought types, the differences between them are higher for SPI than SPEI in what concerns the decadal frequency. For the mean drought duration, the differences are less pronounced, however for SPI and SPEI for the 24-month accumulation period the spatial distributions show higher differences (Figure 3.2b). Similar results are found in the root mean squared error. Observing the Figure 3.1b and Figure 3.3b, both SPI and SPEI for the 24-month accumulation period shows some areas with mean event duration higher than 14 months in Iberia01 dataset, whilst for the multi-model ensemble the mean duration does not surpass 12 months. Despite these differences, the spatial patterns of moderate, severe, and extreme drought frequency and duration are well represented by the multi-model ensemble, which provides the necessary confidence to use this ensemble to characterise the future drought conditions over Iberian Peninsula.

For historical climate, both SPI and SPEI (Figure 3.3a, top panel) show similar spatial patterns for decadal frequency of moderate droughts on all timescales, with SPEI revealing slightly higher frequencies for the 1- month timescale. In the case of severe droughts (Figure 3.3a, middle panel) SPI and SPEI spatial patterns resemble a lot, showing slightly larger values for SPEI than SPI for most of the temporal scales (except for the 6-months). In the case of extreme droughts (Figure 3.3a, bottom panel), SPI shows slightly higher decadal frequencies on all time scales. As expected, smaller timescales show larger decadal frequencies, independently of the analysed index. When analysing both SPI and SPEI for the same timescale, decadal frequencies are larger on the western coast and north-western areas. The frequencies of moderate drought peak at decadal values above 26 events for the one-month scale in the northwest, and at the 24-months scale values ranging mostly between 4 and 6. For extreme droughts, the decadal frequency of events broadly varies from 5 events at the 3-monthly scale to above 2 events on the yearly scale (12-monthly scale).

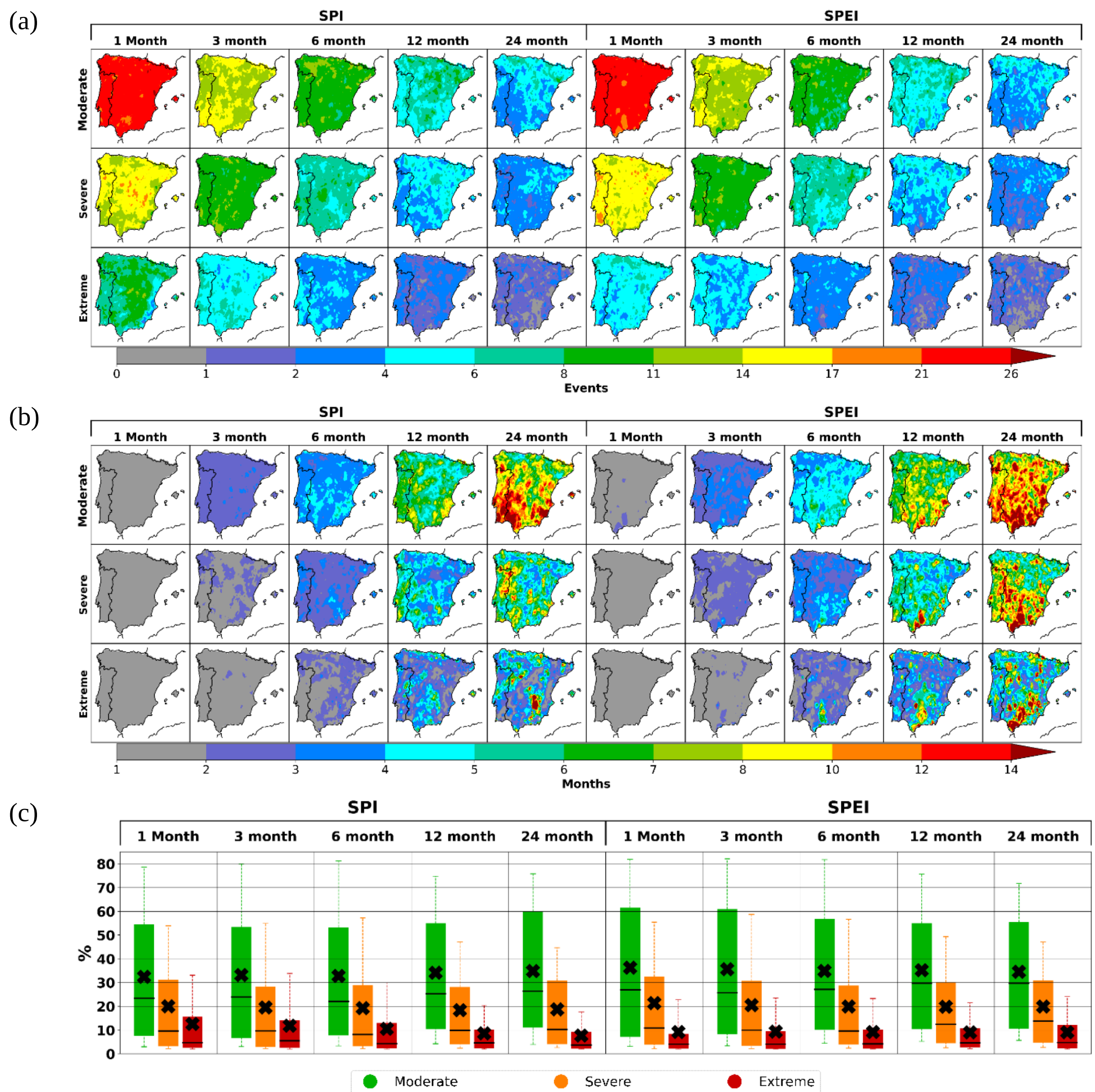


Figure 3.1 Drought (a) decadal frequency, (b) mean duration and (c) spatial extend distribution for the SPI and SPEI from Iberia01 observational dataset for the 1-, 3-, 6-, 12- and 24- months accumulation for the 1971-2000 period. Moderate, severe, and extreme drought are derived from SPI/SPEI values below -0.5, -1 or -1.5, respectively.

Table 3.1 Mean spatial bias between the EURO-CORDEX model ensemble against the Iberia01 observational dataset for (a) drought decadal frequency and (b) drought mean event duration for the 1971-2000 period. (c) and (d) display the root mean squared error for the drought decadal frequency and for the mean event duration, respectively. These results feature the SPI/SPEI index at the 1-, 3-, 6-, 12-, and 24-month accumulation period.

(a)

	Moderate	Severe	Extreme
SPI 1	1.36	0.37	-0.43
SPI 3	0.02	-0.38	-0.35
SPI 6	-0.25	-0.18	-0.18
SPI 12	-0.12	0.03	0.35
SPI 24	0.1	-0.13	0.27
SPEI 1	1.81	1.07	0.85
SPEI 3	0.34	0.17	0.26
SPEI 6	0.35	0.3	0.12
SPEI 12	0.47	0.45	0.32
SPEI 24	0.75	0.54	0.26

(b)

	Moderate	Severe	Extreme
SPI 1	-0.08	-0.08	-0.06
SPI 3	0.02	0.08	0.12
SPI 6	0.16	0.16	0.32
SPI 12	-0.06	0.17	0.29
SPI 24	-0.78	0.85	1.01
SPEI 1	-0.17	-0.11	-0.12
SPEI 3	-0.08	-0.02	0.02
SPEI 6	-0.13	-0.03	-0.06
SPEI 12	-0.68	-0.56	-0.62
SPEI 24	-2.46	-1.51	-1.1

(c)

	Moderate	Severe	Extreme
SPI 1	**2.06**	**1.61**	**1.55**
SPI 3	**1.14**	**1.1**	**0.95**
SPI 6	**1.47**	**1.06**	**0.77**
SPI 12	**1.37**	**1.11**	**0.79**
SPI 24	**1.37**	**0.97**	**0.65**
SPEI 1	**2.46**	**1.72**	**1.29**
SPEI 3	**1.37**	**1.22**	**0.82**
SPEI 6	**1.54**	**1.24**	**0.76**
SPEI 12	**1.41**	**1.28**	**0.79**
SPEI 24	**1.49**	**1.15**	**0.69**

(d)

	Moderate	Severe	Extreme
SPI 1	0.12	0.12	0.1
SPI 3	0.22	0.24	0.26
SPI 6	0.6	0.54	0.57
SPI 12	1.42	1.39	1.45
SPI 24	3.69	2.6	3.27
SPEI 1	0.21	0.15	0.18
SPEI 3	0.34	0.34	0.35
SPEI 6	0.91	0.78	1.06
SPEI 12	2.26	2.59	2.62
SPEI 24	6.47	5.22	4.95

(a)

(b)

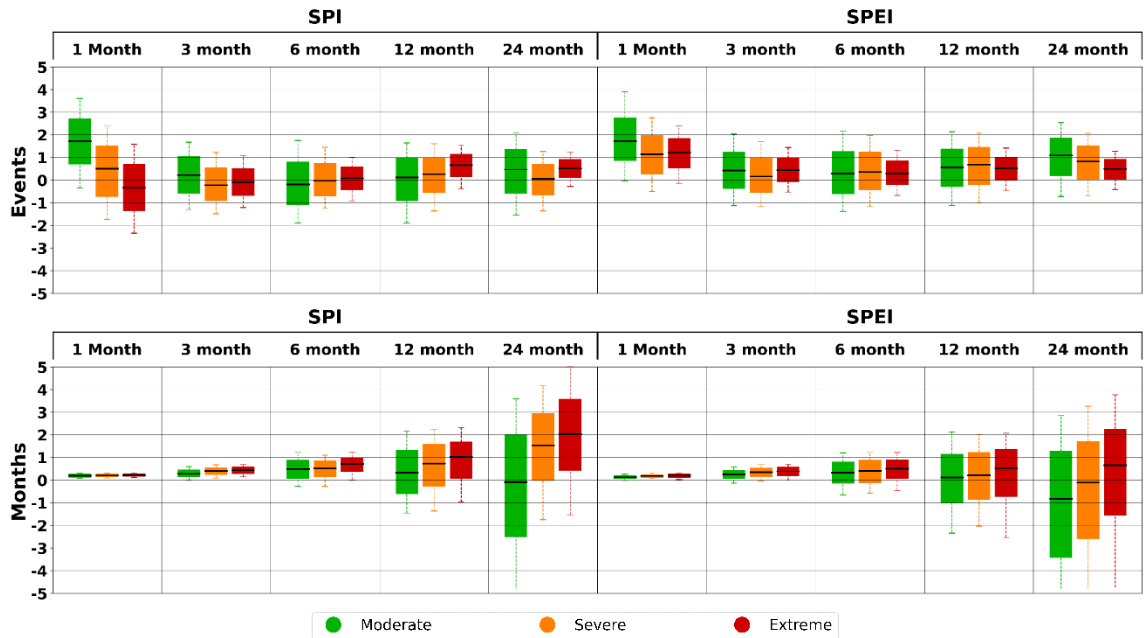


Figure 3.2 Boxplot of the spatial distribution of the bias between the EURO-CORDEX models and the Iberia01 observational dataset for the 1971-2000 period, where (a) shows the results for the decadal frequency of events and (b) the mean event duration. These results are for the SPI/SPEI at the 1-, 3-, 6-, 12-, and 24-months accumulation period.

During the 1971-2000 period, droughts show higher values of duration when computed using SPEI (Figure 3.3b), with a similar spatial characterization relative to SPI. Droughts with longer durations are found in the Iberian north-eastern and south-eastern regions, reaching 14 months long in some areas for moderate droughts and above 8 months for severe drought. Those durations refer to the 24-month accumulation drought time scales.

In terms of the spatial extent of drought for the 1971-2000 period (Figure 3.3c), all accumulation time scales reveal similar distributions in each moderate, severe, or extreme drought type. For the SPEI, the distribution has slightly more variability reaching 80% of the Iberian Peninsula in drought for the 90th percentile (high whisker). In general, the drought spatial extent is lower than 20% and 10% of the Iberian territory for severe and extreme droughts, respectively.

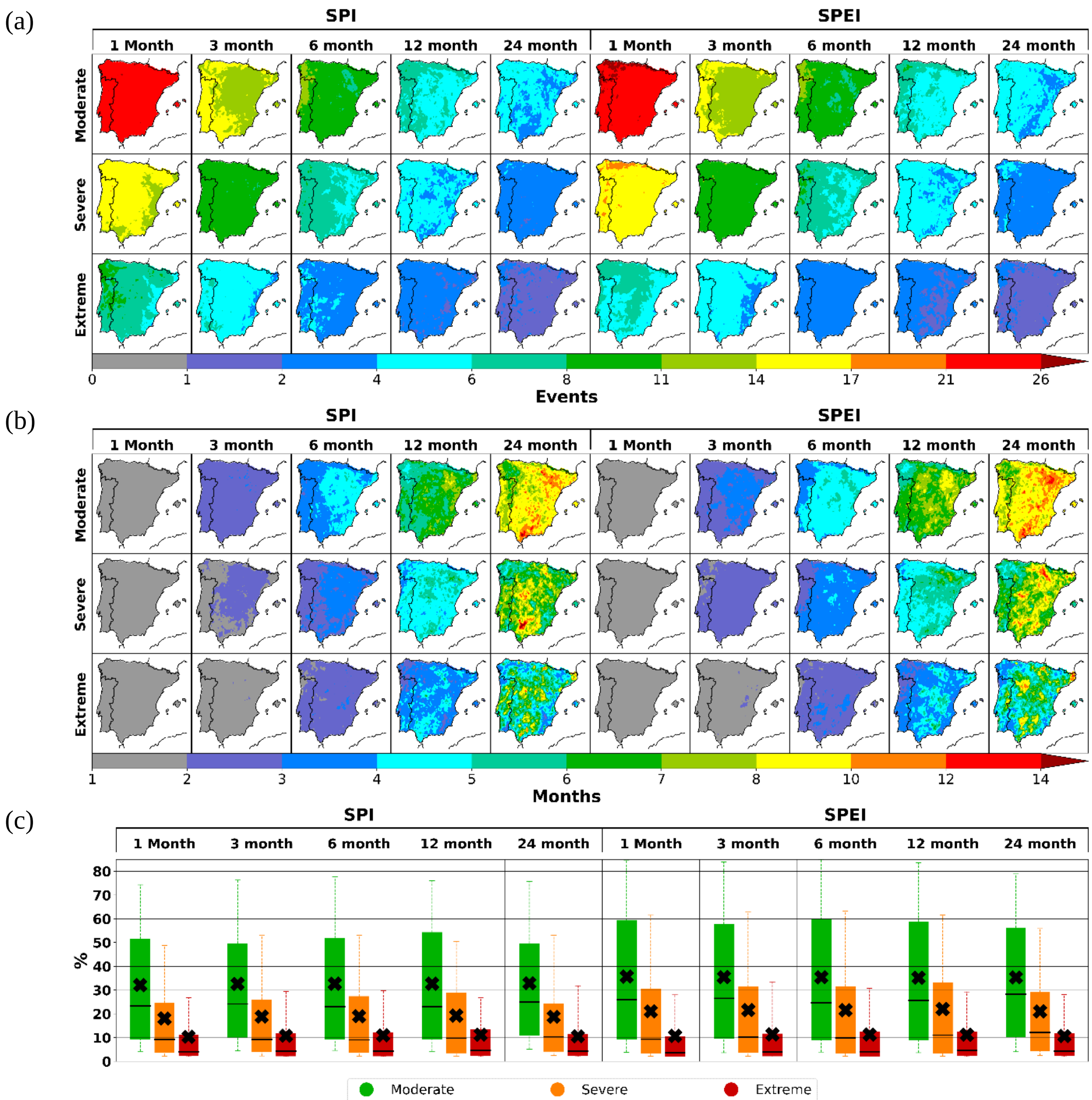


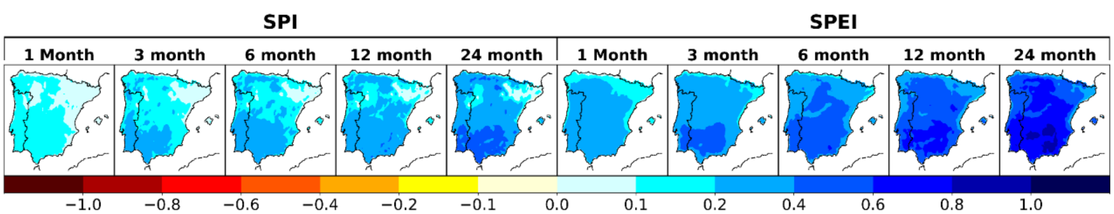
Figure 3.3 EURO-CORDEX (a) drought decadal frequency, (b) mean drought duration and (c) boxplots of the spatial extent of the monthly drought for the SPI and SPEI (in percentage of the Iberian mainland territory) from the weighted multi-model ensemble for the 1-, 3-, 6-, 12- and 24-months accumulation for the 1971-2000 period. Moderate, severe, and extreme drought stands for SPI/SPEI values below -0.5, -1 or -1.5, respectively. For this figure, all indexes were computed only in the 30-year period from 1971 to 2000. In the boxplots, the lower whisker value denotes the 10th percentile and the higher whisker the 90th percentile.

3.2. Multiple scenarios

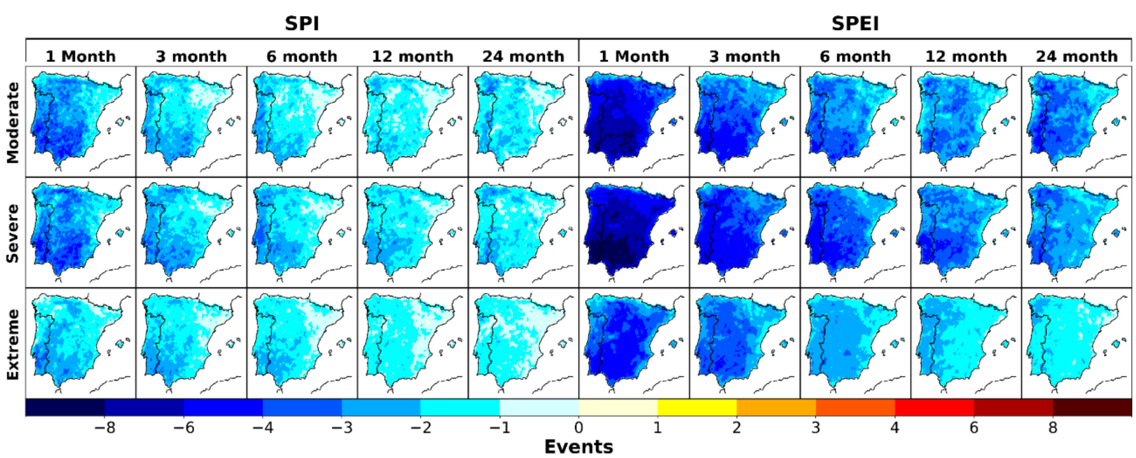
The SPI and SPEI indexes in this section are built from a 300-year period, thus featuring the historical 1971-2000 and the 2011-2100 from all RCP scenarios. Thus, differences arise relative to the results shown in the previous section. Figure 3.4 displays those differences for the 1971-2000 time slice, which stand for the historical period. Overall and as expected, the reference period with the 300-year indexes reveals a more humid panorama, underestimating droughts on the current climate. For instance, Figure 3.4a displays the differences of the mean value, with higher values among all timescales, especially for the higher periods. Figure 3.4b and 3.4c shows, overall, negative differences for the decadal frequency and for mean duration of droughts. Those differences imply less frequent and shorter events for the reference period from the 300-year indexes in comparison with the 30-year indexes. These differences are more evident for the shorter timescales for the decadal frequency, while for the mean drought duration the higher differences occur for the longer timescales.

Regarding future drought intensity (Figure 3.5) both indices reveal a clear shift to larger drought intensities when considering the RCP2.6 to RCP4.5 and RCP8.5. This shift agrees with the known future projections of rainfall reduction and temperature increase, with the latter included on SPEI for Iberia (Soares et al. 2017a; Cardoso et al. 2019; Argueso et al. 2012; Cos et al. 2022). Moreover, responding to the projected rising temperatures, SPEI indicates larger anomalies of intensities than SPI, as expected. A clear shift with time throughout the century for higher negative values is not seen within all RCPs. In fact, this only occurs for RCP8.5.

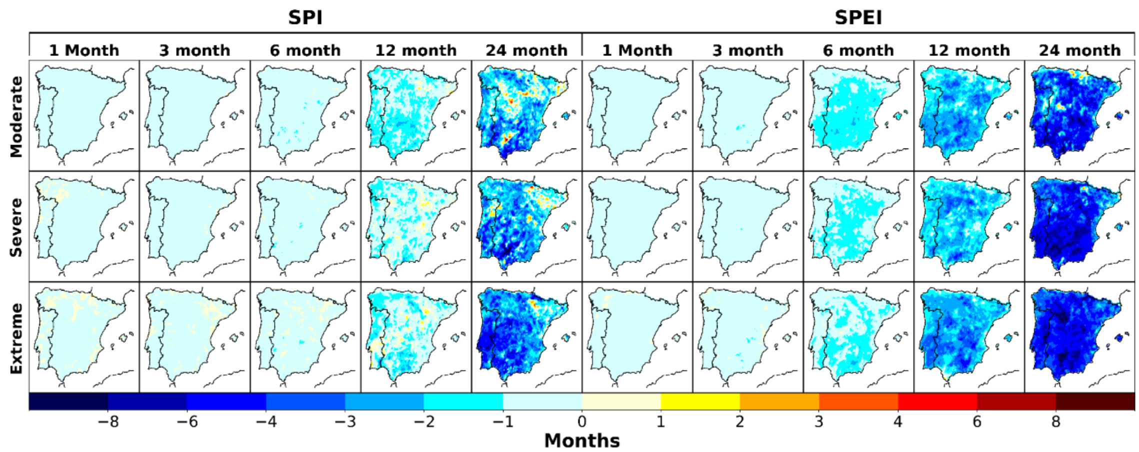
(a)



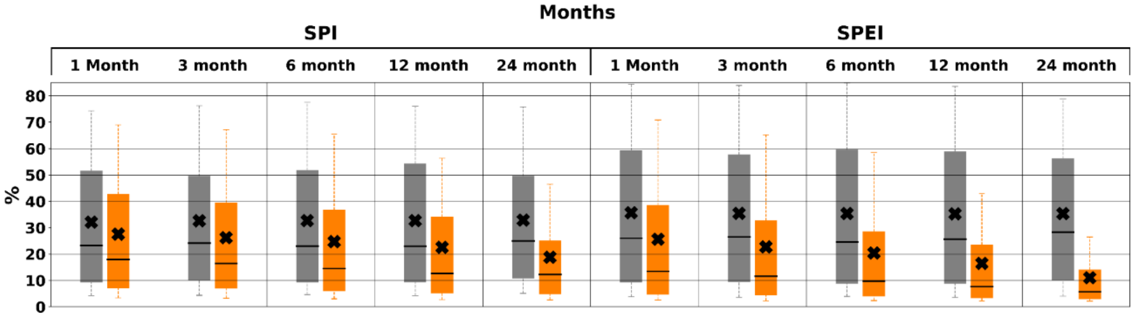
(b)



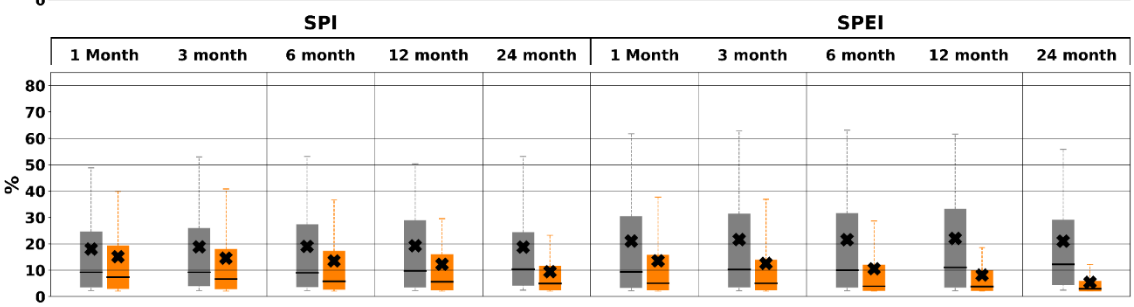
(c)



(d)



(e)



(f)

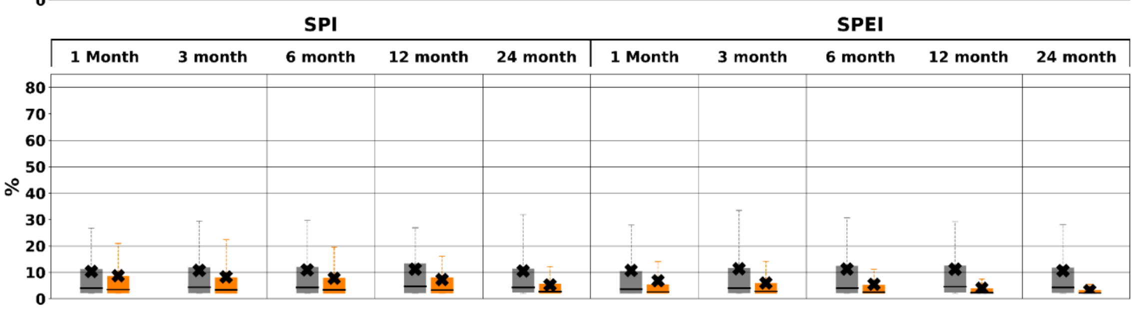


Figure 3.4 Difference across the historical period references (1971-2000) extracted from the joint 300 year period featuring all RCP scenarios (RCP2.6, RCP4.5 and RCP8.5) against the historical results obtained in Figure 3.1 for the current climate, where SPI and SPEI were computed only considering the 1971-2000 period. The panels show the differences for the (a) mean index value, (b) decadal frequency, and (c) mean event duration. These results are computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24-months accumulation period. Panels (d) for moderate, (e) for severe and (f) for extreme drought displays the spatial extent within each drought type for each timescale in percentage of the Iberian mainland territory, where the grey boxplots (left) are for the 1971-2000 period from the 30-year index, while the orange boxplots denote the reference period from the 300-year indexes. For all boxplots the cross denotes the mean value of the spatial extent across the whole period.

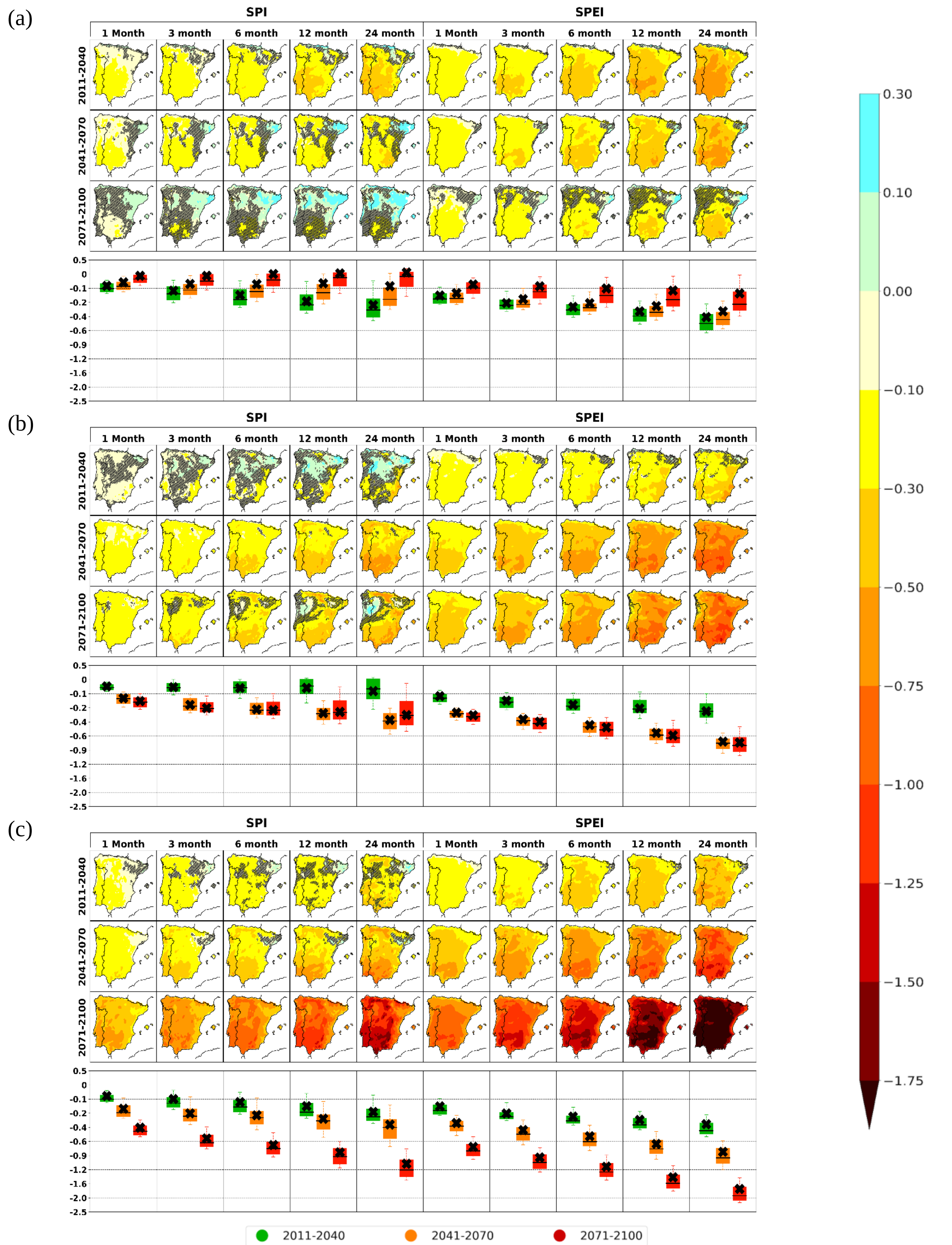


Figure 3.5 Differences in drought intensity between the early (2011-2040), mid (2041-2070) and end (2071-2100) century relative to the historical reference period (1971-2000) from each scenario for the EURO-CORDEX.

For every panel the differences are obtained by averaging the 30-year period from each model and the ensemble is then built by considering the weights in Table 2.1. These results are computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24- months accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch's t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.

Looking at the anomalies of drought intensities for the RCP2.6 (Figure 3.5a), SPI and SPEI points to an increase until the mid-century and a reduction for the end-of-century of drought intensity in some areas of the Iberian Peninsula and for all drought timescales. These positive anomalies are considerably higher for SPEI than SPI. Moreover, in the case of SPI for 2071-2100 the projected positive anomalies correspond to an attenuation of drought intensities. SPEI anomalies show a small increase of drought intensity for all periods, but being milder for the end-of-century, in general smaller than -0.5.

For the intermediate scenario (RCP4.5, Figure 3.5b), drought intensity time evolution shows a monotonous increase for SPEI, but with similar changes for mid and end century. For the shorter drought scales (1 to 6 months) those increases are up to -0.75 confined mostly to the southern areas. For the longer droughts' scales (12 to 24 months), the anomalies reach a much larger value, up to -1 for SPEI, in a large extension of southern Iberia, for the end-of-century. The differences between RCP2.6 and RCP4.5, for one- and two-year(s) droughts (12 and 24 months), at the end-of-century are notorious. For SPEI, in the former case, drought intensities are projected to reach at most -0.75 in small areas scattered in Iberia, and in the latter case anomalies above those values can reach -1.25 over large portions of the Iberian mainland. Examining the RCP8.5 results (Figure 3.5c), the monotonous increase in drought intensity is greatly enhanced with the increased drought timescale and throughout the century, according to both indices. SPEI for 12- and 24-months scales point to intensity anomalies rather severe, which attain values above -1.5 in 2071-2100, corresponding to approximately 5x with respect to the 2011-2040 period. By far, the results for the RCP8.5 are much more severe when compared to the other scenarios, even for mid-century. In line with the major differences on the reported drought intensity increases among two of three RCPs (RCP4.5 and RCP8.5), the drought decadal intensity evolution for the 21st century is extremely worrying.

Figure 3.6 reveals the projections for the future anomalies of drought decadal frequencies for severe drought in Iberia. Similarly, Figure 3.7 and Figure 3.8 show the drought decadal frequencies, respectively, for the projected anomalies of moderate and extreme drought. The examination of the SPI and SPEI results for all RCPs show an aggravation of the decadal occurrence of drought events at all time scales but particularly at the shorter ones. In the high-end case, for the RCP8.5 and at the end-of-century, the increases surpass 15 (9) occurrences in a decade on the 1-month time scale as indicated by SPEI (SPI). These are followed closely by the other time scales, from 3- to 24-months, for which a troubling growth of more than 9 down to 3 drought events per decade, respectively, are projected.

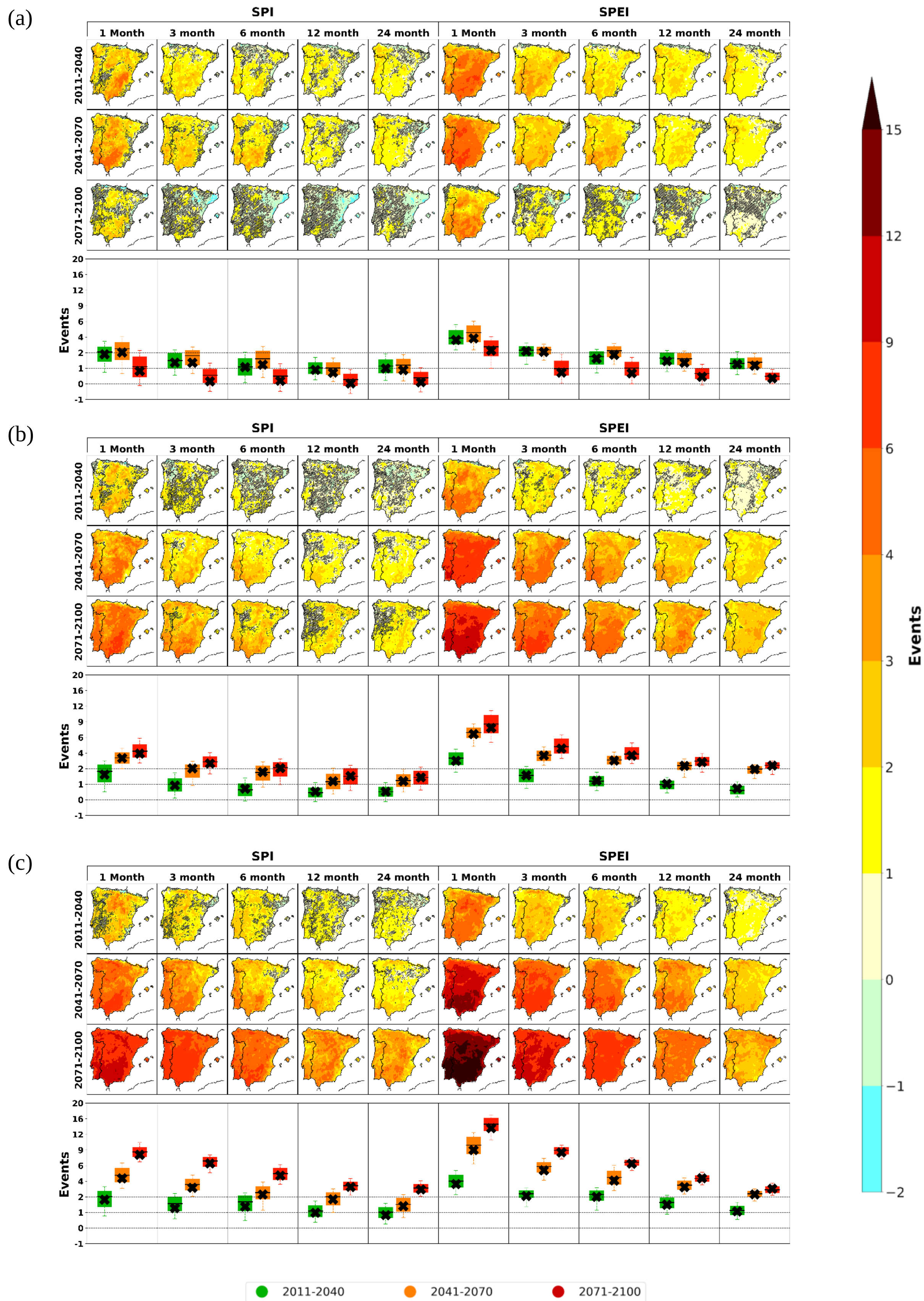

(a)
(b)
(c)
SPI
SPEI
1 Month
3 month
6 month
12 month
24 month
2011-2040
2041-2070
2071-2100
Events
2011-2040
2041-2070
2071-2100

Figure 3.6 Differences of severe drought (SPI and SPEI below -1) decadal frequency, between the early (2011-2040), mid (2041-2070) and end (2071-2100) of century, relative to the historical reference period (1971-2000) for the EURO-CORDEX. For every panel the differences are obtained by considering the weighted multi-model ensemble. These results are computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24- months accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The panels with boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.

It is highly relevant to acknowledge the large discrepancy on the anomalies of drought decadal frequencies from RCP8.5 to RCP2.6, which strikingly point to completely different impacts and adaptation challenges. Moreover, SPI and SPEI show different increments, with the differences of severe drought decadal frequency depicted by SPEI being far larger than SPI, which are a result of SPEI trends being generally larger due to the regional warming effect (Páscoa et al. 2021). Based on the SPEI index which presents the mild-case scenario when it comes to the analysed indices (Figure 3.6), within the RCP2.6 an increase of severe drought is projected for the near- and mid-century followed by a reduction at the end-of-century, for all drought timescales. The mid-century increase is particularly large for the 1-month scale, with the difference being of around 6 more events per decade for most of Iberia. From 3 months to 2 years, increases between 1 and 3 events are projected for a large extent of the peninsula. For the 2071-2100 period a slight reduction in the increase of drought events is revealed, with 4 to 6 more events over large areas of the southern Peninsula at the 1-month timescale and an increase of at most 2 events for the other timescales. For the RCP4.5 scenario changes in severe drought frequency are projected to grow throughout the century reaching values above 9 for the 1-month scale. This increase is progressive throughout the 21st century. For the 3- to 12-months scales, the future anomalies reach above 6 events in large extensions of Iberia. These augments reflect a massive growth of drought occurrence in Iberia, which corresponds to multiplying by 2 and 3 the decadal frequency of severe droughts for the mid- and the end-of-century, respectively, when compared to the near future climate, for vast areas of Iberia.

For moderate drought the projected increases are larger for short drought scales, such as 1 and 3 months, reaching anomalies around 10 for the RCP8.5 and end-of-century (Figure 3.7). Under the RCP2.6, a slight variation in the decadal frequency of moderate droughts is observed throughout the 21st century, up to 3 (9) more events for SPI (SPEI). For the RCP4.5 and RCP8.5 a rising in decadal frequency is presented from mid-century, stronger for the non-mitigation scenario, from 3 (3) up to 9 (12) more moderate droughts considering the SPI (SPEI). In what concerns the projected evolution of extreme droughts, the results follow the ones shown for severe drought, but with maximum anomaly values in the range of 4 in RCP2.6, 6 in RCP4.5 and 9 in RCP8.5 considering the SPI (Figure 3.8).

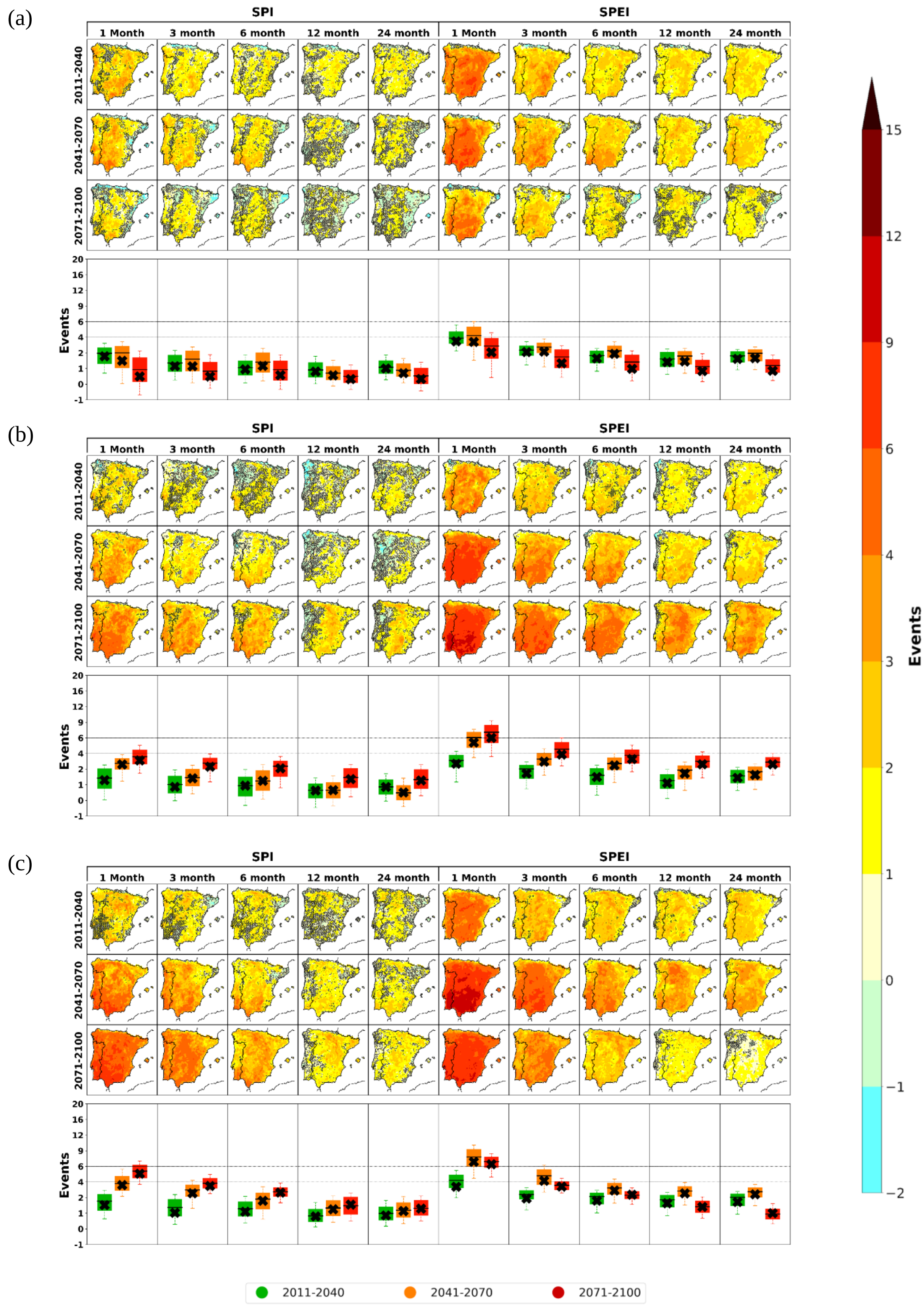
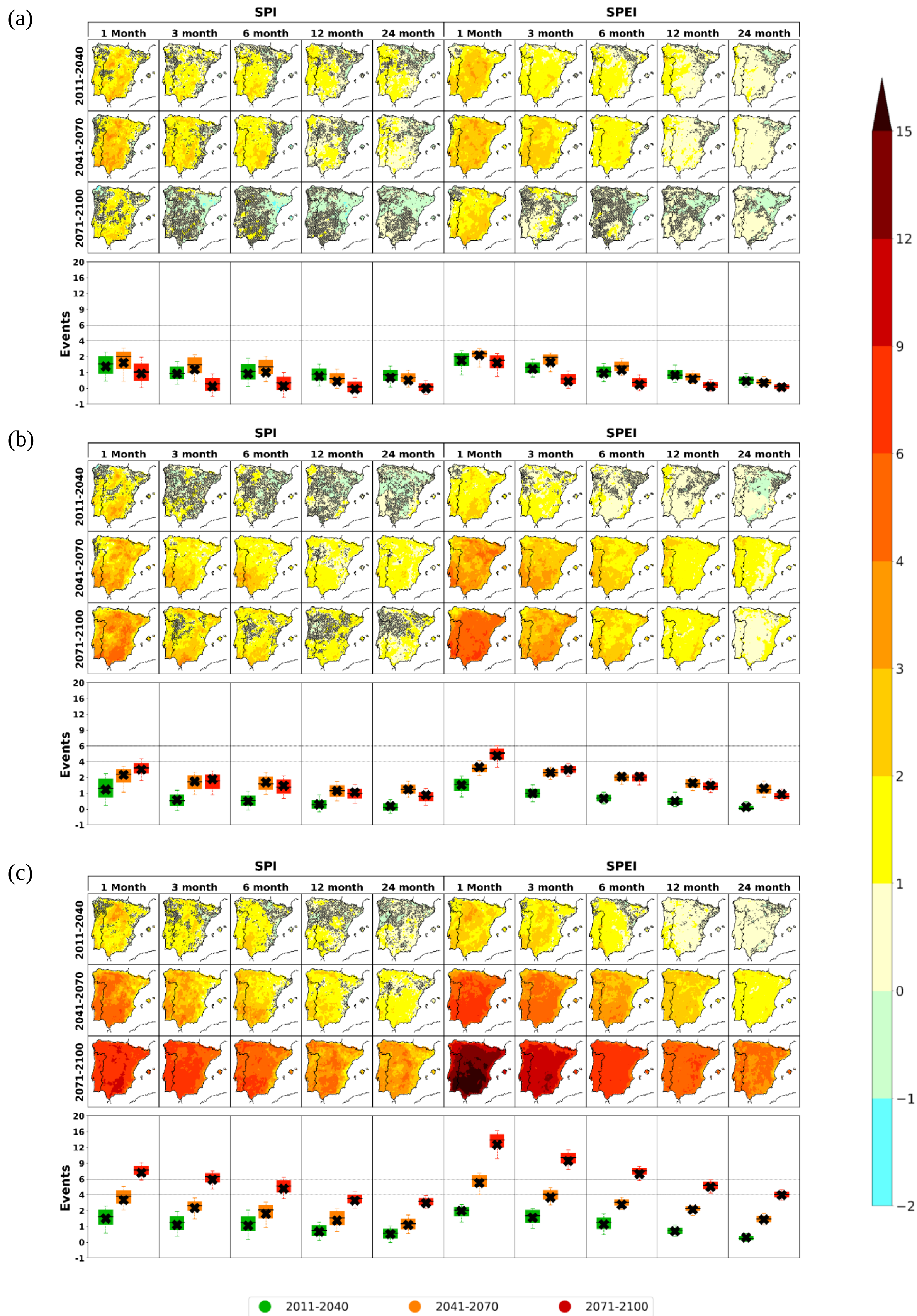

(a)
(b)
(c)
SPI
SPEI
1 Month
3 month
6 month
12 month
24 month
2011-2040
2041-2070
2071-2100
Events
2011-2040
2041-2070
2071-2100

Figure 3.7 Differences of moderate drought decadal frequency (SPI and SPEI below -0.5), between the early (2011-2040), mid (2041-2070) and end (2071-2100) century, relative to the historical reference period (1971-2000) for the EURO-CORDEX. For every panel the differences are obtained by averaging the decadal frequency from each model 30-year period and computed for each index SPI and SPEI at 7 at 1-, 3-, 6-, 12- and 24- month accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The panels with boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.



(a)
(b)
(c)
SPI
SPEI
1 Month
3 month
6 month
12 month
24 month
2011-2040
2041-2070
2071-2100
Events
2011-2040
2041-2070
2071-2100

Figure 3.8 Differences of extreme drought decadal frequency, (SPI and SPEI below -1.5), between the early (2011-2040), mid (2041-2070) and end (2071-2100) century, relative to the historical reference period (1971-2000) for the EURO-CORDEX. For every panel the differences are obtained by averaging the decadal frequency from each model 30-year period and computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24-month accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The panels with boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.

Regarding the changes on severe drought mean event duration, for the three periods and the three RCPs, exceptional differences amongst emission scenarios and periods are depicted in Figure 3.9. The changes are characterised generally by being greater for the longer timescales for both SPI and SPEI, with SPEI showing larger increments, independently of the emission scenario and for the three time periods. For RCP2.6, SPI reveals rather small increases or decreases for the severe drought durations, particularly at the end-of-century. SPEI reveals at the most increases which can reach between 5 and 10 months for the 24-month accumulation period. Moreover, for the RCP2.6, similar anomalies are displayed for the near- and mid-century cases, and even smaller amounts for the end-of-century. For RCP4.5 the highest mean duration differences are seen for the mid-century, reaching values higher than 10 months in the centre of Iberian Peninsula for the 24-month timescale. For the lower drought timescales, the increase is not so intense, ranging from no change (for the scales 1 to 3 months) to 3-5 months (for the scales between 6-months and 1-year). For the beginning and end-of-century, SPI shows heterogeneous anomalies, with some areas of the Peninsula revealing increases, while others display decreases. Conversely, SPEI mostly shows a consistent increase of mean duration for all the timescales both in the beginning and end-of-century, although for the end-of-century milder changes are expected (ranging from no change at the shorter timescales of 1 to 3 months and approximately an increase of 3-10 months for the 24-months accumulation), in comparison to the mid-century. Finally, regarding the RCP8.5, both SPI and SPEI generally show a consistent and important increase of mean duration for the longer timescale throughout the 21st century. These longer lasting drought increments change rather monotonously. For the 6-month drought timescale the mean durations are added up to 5 months, the one-year up to 15 and the 24-month above the 40 months over large areas of the domain for the end-of-century.

(a)

(b)

(c)

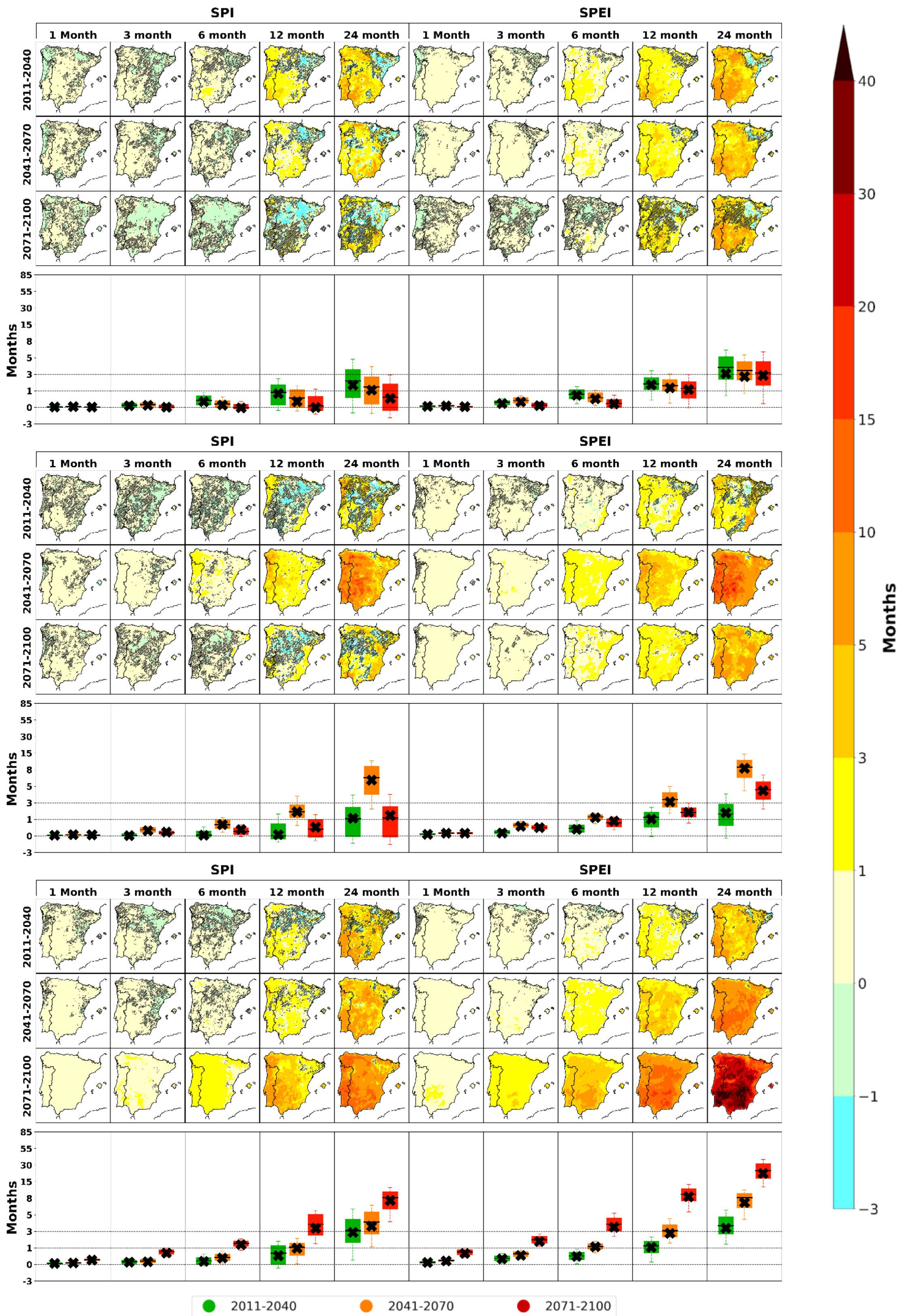


Figure 3.9 Differences of mean severe drought duration (SPI and SPEI below -1) between the early (2011-2040), mid (2041-2070) and end (2071-2100) century, relative to the historical reference period (1971-2000) for the

EURO-CORDEX. For every panel the differences are obtained by considering the weighted multi-model ensemble. These results are computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24- month accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The panels with boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.

Regarding the moderate and extreme drought mean event duration (Figure 3.10 and Figure 3.11, respectively), the change patterns follow the ones observed for severe drought events. For moderate drought, differences in mean duration are quite significant for the RCP4.5 and RCP8.5 from mid- to end-of-century. For the RCP4.5, the mean event duration can reach more than 10 (15) months in the mid-century 12-month timescale (24-month timescale). For the RCP8.5, in the mid-century, the moderate drought events can reach increases in average duration of 20 (30) months for the 24-month timescale considering the SPI (SPEI). Notice that the projected changes in average duration of moderate drought events is more pronounced in longer timescales than for shorter ones. For the RCP2.6 scenario, significant differences are found for the mid-century and for longer timescales, reaching more 5 (10) months in event duration for SPI (SPEI) considering the 24-month accumulation period. Similarly, it is expected an increase in average duration of extreme drought events, reaching more 5 months in RCP2.6, 15 months in both RCP4.5 and RCP8.5 considering the SPI and 24-months timescale.

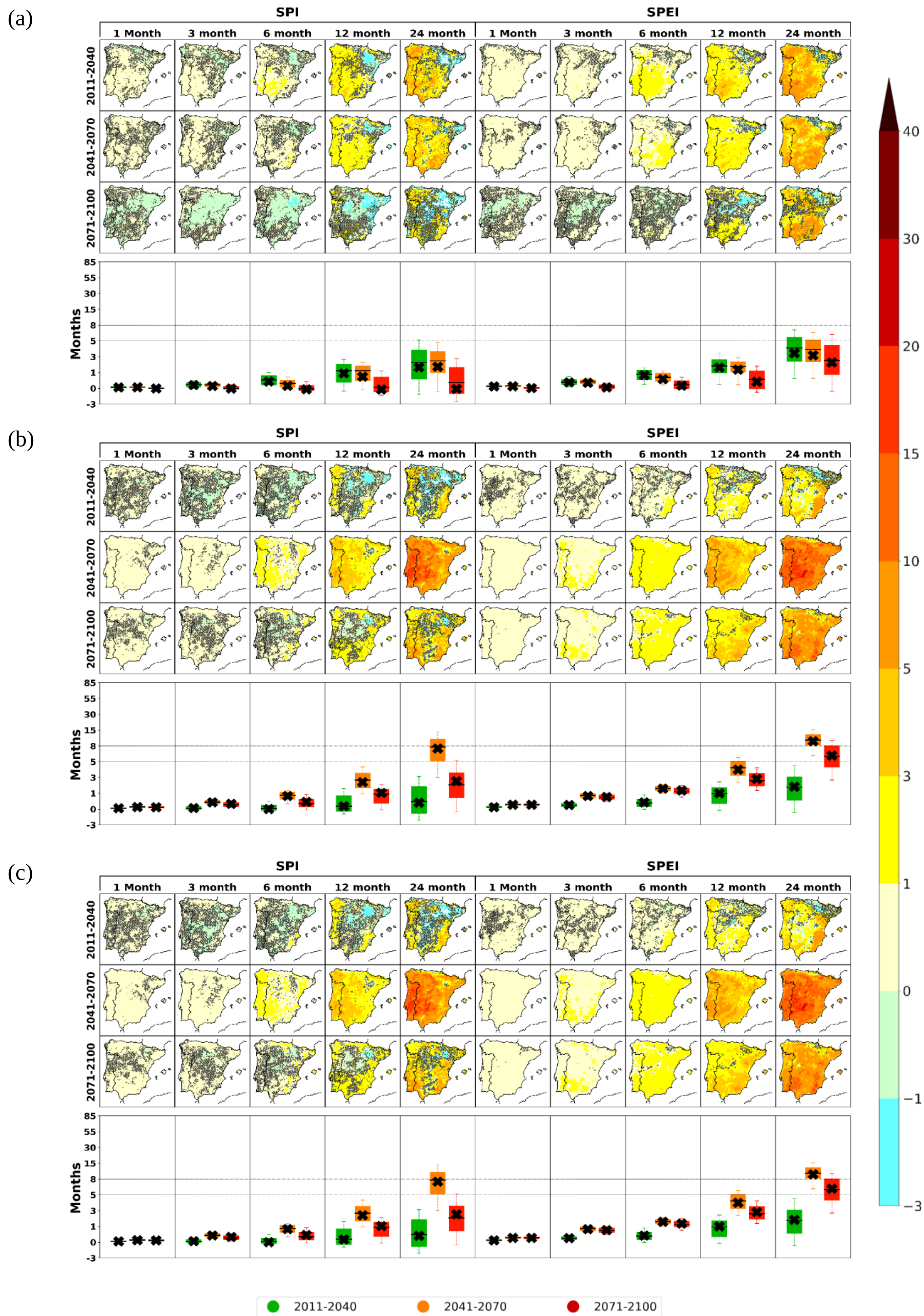

(a)
(b)
(c)
SPI
SPEI
1 Month
3 month
6 month
12 month
24 month
2011-2040
2041-2070
2071-2100
Months
85
55
30
15
8
5
3
1
0
-3
40
20
10
−1
2011-2040
2041-2070
2071-2100

Figure 3.10 Differences for mean moderate drought duration (SPI and SPEI below -0.5) between the early (2011-2040), mid (2041-2070) and end (2071-2100) century, relative to the historical reference period (1971-2000) for the EURO-CORDEX. For every panel the differences are obtained by considering the weighted multi-model ensemble. These results are computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24- month accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The panels with boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.

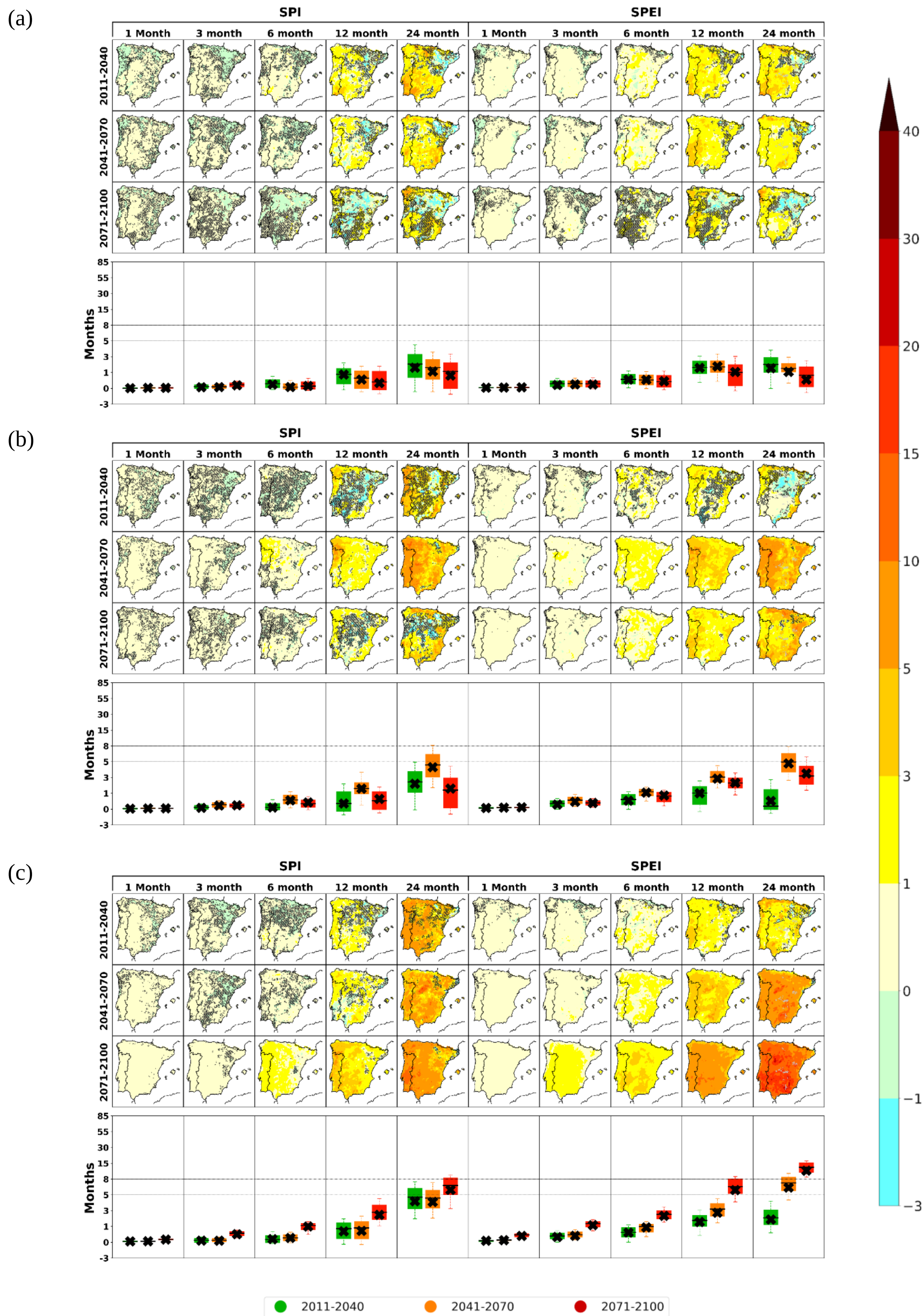

(a)
(b)
(c)
SPI
SPEI
1 Month
3 month
6 month
12 month
24 month
2011-2040
2041-2070
2071-2100
Months
85
55
30
15
8
5
3
1
0
-3
40
20
10
−1
Months
2011-2040
2041-2070
2071-2100

Figure 3.11 Differences for mean extreme drought duration (SPI and SPEI below -1.5) between the early (2011-2040), mid (2041-2070) and end (2071-2100) century, relative to the historical reference period (1971-2000) for the EURO-CORDEX. For every panel the differences are obtained by considering the weighted multi-model ensemble. These results are computed for each index SPI and SPEI at 1-, 3-, 6-, 12- and 24- month accumulation period. The dark-grey dots denote points where these differences are not statistically significant at the 5% significance level following the Welch t-test. The results follow the (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 scenarios. The panels with boxplots resume the information from the previous panels, where the low whiskers denote the 10th percentile and the high whisker the 90th percentile. The cross denotes the mean spatial value.

Figure 3.12 displays the evolution of the spatial extent (in percentage of mainland Iberia) for moderate, severe, and extreme droughts, only for SPEI at the 12-month timescale. The projections for all the other accumulations and for the SPI index reveal similar results and similar conclusions may be inferred. As expected, the percentage of area in drought decreases from moderate to extreme droughts. Focusing on severe droughts (Figure 3.12b) the projected changes are in line with the previous results (Figure 3.5, Figure 3.6 and Figure 3.9). The differences of the future changes amongst the three emission scenarios are striking. For the RCP2.6, the boxplots reveal higher percentage of area in drought at the beginning of the century and progressively reducing towards the end, reaching similar values relatively to the historical reference period. As for the RCP4.5 the spatial variability peak occurs at the mid-century, slightly decreasing for the end-of-century. As expected, it is for the RCP8.5 where the largest changes in drought spatial extension are projected, with a progressively increase towards the end of the 21st century, surpassing in mean 50% of area in severe drought. For comparison, the high whisker for the historical reference period do not reach the 20% of area in drought, while for the end-of-century RCP8.5, the low (high) whisker has values of 10% (above 90%).

For the moderate and extreme droughts (Figure 3.12a and c), similar future spatial extensions can be found. Notice however, at the end-of-century, for the RCP8.5 scenario, the mean of the percentage of area in moderate drought can surpass the 70% of the territory. Overall, the tendency of changes for moderate drought is similar as for severe drought. Considering the extreme drought, also for the end-of-century RCP8.5 scenario, the mean reveals more than 30% of land in extreme drought, contrasting with the other periods and scenarios. Indeed, this increase in area is noteworthy, even when comparing with the moderate and severe droughts.

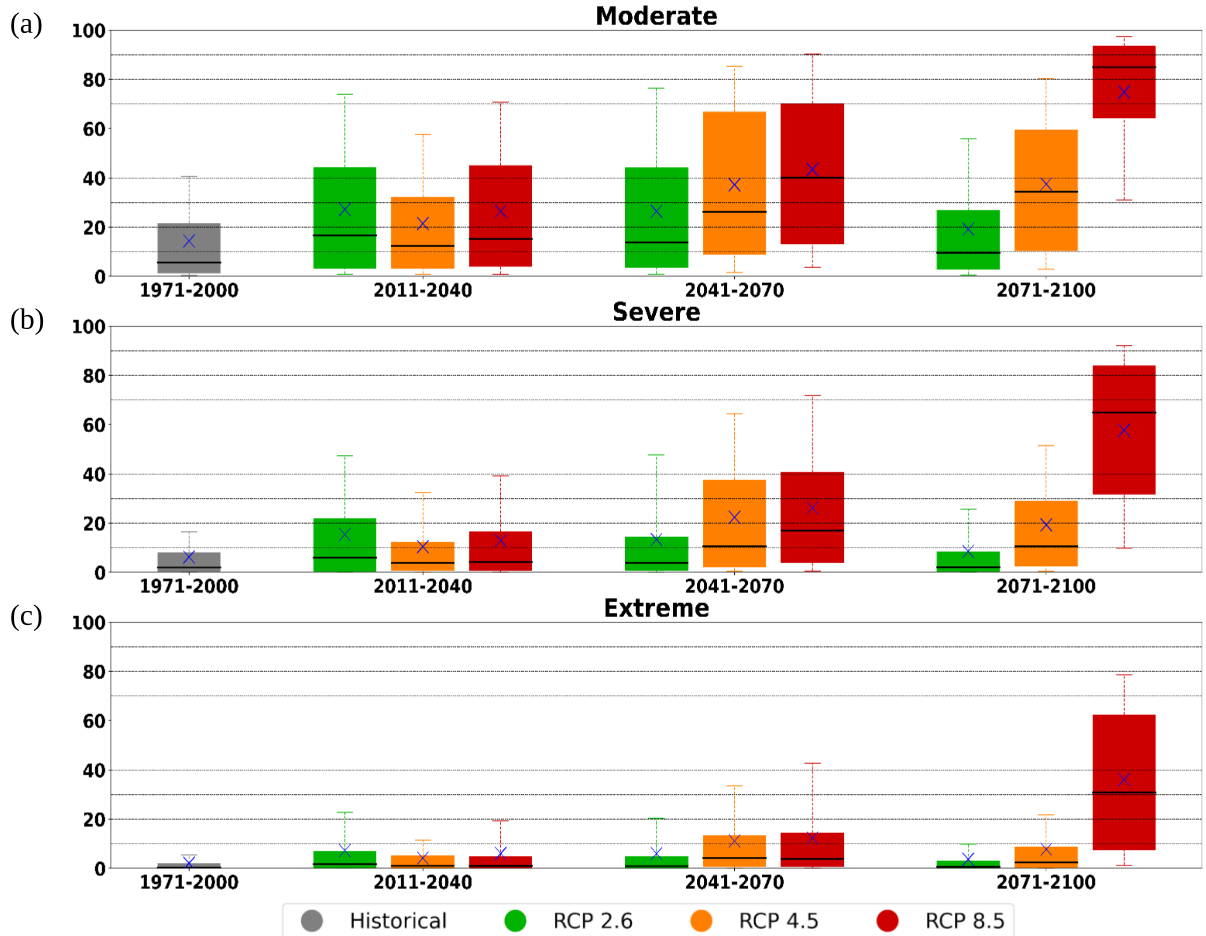


Figure 3.12 Evolution of the spatial extent in percentage for (a) moderate, (b) severe and (c) extreme drought, (in percentage of the Iberian mainland territory) considering the 12-month accumulation SPEI index. Each boxplot represents the distribution of the monthly area in drought for the Historical reference period (1971-2000), near future (2011-2040), mid-century (2041-2070) and end-century (2071-2100). For all boxplots, each cross denotes the mean value of the percentage of area in drought.

4. Discussion

In the present study, the analysis of the evolution throughout the 21st century of droughts and their main properties over Iberia was performed, based on a weighted multi-model ensemble of EURO-CORDEX high-resolution simulations (Lima et al. 2023), including three RCPs scenarios from high- to non-mitigation: RCP2.6, RCP4.5 and RCP8.5 (van Vuren et al. 2011). The main goal of this study was to feature the dissimilarities of droughts arising from the different RCP emission scenarios and making clear the diverse adaptation needs associated.

Droughts are examined based on the monthly timescale indices SPI and SPEI, computed for 1- to 24-months accumulation periods for two climate periods, 1971-2000 for historical climate, and the 1971-2100 encompassing the end of the 20th century and the full 21st century from 2011-2100 for all RCPs. SPI and SPEI reflect the changes in drought characteristics (intensity, decadal frequency, mean event duration and spatial extension evolution) projected to occur in Iberia. Then future drought anomalies were compared to the historical reference period climate for three future climatology periods (2011-2040; 2041-2070 and 2071-2100).

As highlighted by several studies over Iberian Peninsula, the projections point out for significant changes in climate conditions, expecting warming and drying trends throughout the end of the 21st century (Cramer et al., 2018; Giorgi, 2006; Lionello and Scarascia, 2018; Tuel and Eltahir, 2020; Soares et al. 2017; Cardoso et al. 2019; Lima et al. 2023; Soares and Lima 2022; etc…). Aligned with the severe projections of regional warming and precipitation reductions, it is expected changes on the frequency, duration, and spatial distribution of the extreme events, such as droughts. In addition, in response to these projections, a strong decrease in soil moisture is projected, which may lead to an intensification of heatwaves and droughts (Soares and Lima 2022). The future projections point to more severe, longer, and more spread-out drought events over Iberia Peninsula throughout the 21st century, with striking differences amongst the emission scenarios. Considering a strong mitigation scenario (RCP2.6), the future drought projections are much less severe, while being especially dramatic for the non-mitigated emission scenario (RCP8.5). Indeed, the projected warming and drying conditions are more severe for high anthropogenic emission scenarios (Barcikowska et al., 2018; Cramer et al., 2018; Lima et al. 2023). For the RCP2.6, significant changes in intensity, frequency and duration of drought events are found mostly in the near or mid-century, linked with the period in which the CO_2 emissions peak, and declining afterwards. This decline is linked to a small precipitation increase and a stabilisation for temperature that is projected for the end-of-century, with respect to the mid-century. In what concerns the RCP8.5 scenario, significant changes are projected throughout the 21st century, with drought events more intense and severe in the end-of-century. For instance, an increase of more than 15 decadal events for the shorter time scale and an increase of 4 for the longer accumulations are projected for severe or extreme droughts. Regarding the mean event duration, the projections reveal small to no changes at 1-month accumulation, while the 24-month accumulation easily surpass an increase in duration superior to 30 months for the severe droughts. As for the spatial extent, it is expected to more than 50% of the Iberian Peninsula to be in severe drought in mean, an increase from 10% from the historical reference period.

Overall, comparing the SPI and SPEI results, it is clear that evapotranspiration plays an important role in the increase of drought frequency and duration in the Iberian Peninsula. This result is consistent with the results from Páscoa et al. (2017, 2021), also from González-Hidalgo et al. (2018) and suggests that the atmospheric evaporative demand is important, and the water supply of the atmosphere has not been sufficient to cope with the water demand, which in turn is amplified by increasing warming conditions (Vicente-Serrano et al. 2014). This is also in accordance with the results of Guerreiro et al. (2017), which show that SPI is not appropriate for semi-arid rainfall regimes such as the one affecting Iberia. The SPEI includes a simplified water balance between precipitation and potential evapotranspiration and therefore accounts for the effect of increasing temperatures, which means that it is dependent on the precipitation and temperature future changes. SPI only depends on the precipitation changes. SPI usually does not reveal such high changes for drought variability, mainly since the precipitation does not exhibit such a significant change as temperature does in Iberia (Páscoa et al. 2021; Cardoso et al. 2019; Soares et al. 2017a; Lima et al. 2023). In regions where the future projections point to a significant reduction in annual precipitation, the frequency of occurrence of moderate to extreme droughts increases, whilst in regions where there are lower changes in the number of moderate to extreme droughts per decade, it is expected negligible changes in annual precipitation (Argueso et al. 2012; Soares et al. 2017a; Lima et al. 2023). The analysis of the number of models which agree in the signal of change also highlight that the inclusion of temperature through potential evapotranspiration in a drought index is therefore paramount to improve the projections. Thus, SPI is insufficient for drought analysis studies over regions where there is a strong warming signal, as the Iberian Peninsula (Ionita and Nagavciuc 2021). In addition, the agreement of the climate change signal among the models may contribute to such differences between the SPI and SPEI. Whilst it is very likely the increase of temperature, changes in precipitation are strongly influenced by natural internal variability worldwide and over Iberia (IPCC 2013, 2021; Soares et al. 2017a).

Comparable findings are also projected by other studies, which use a similar drought index (e.g García-Valdecasas Ojeda et al. 2021; Guerreiro et al. 2017; Spinoni et al. 2018, 2021; Moemken et al. 2022). Nevertheless, the present study goes further than the referred investigations, relying on a weighted multi-variable multi-model ensemble, integrating temperature and precipitation, examining the three CMIP5 RCPs available and including shorter and longer timescales (lower than 3-months and longer than 12-

months). In addition, it is important to emphasize that the scientific approach used and presented in this study is useful for drought assessment on other regions in the world.

5. Final Remarks

The presented results point to substantial different socio-economic impacts and adaptation needs. Even for the most optimistic scenario, an increase in drought frequency and duration is expected, resulting in sectoral impacts on agriculture and water management, and in climate risks as the occurrence of forest fires. Although different adaptation measures should be adopted according to the future emission scenario, management approaches facing crisis situations are still the most common in addressing drought. This will unequivocally fail to strengthen the societies resilience, which will negatively contribute to long-term sustainability.

The current investigation was performed in the framework of the National Roadmap for Adaptation 2100 – Assessment of the Portuguese territory's vulnerability to climate change in the 21st century (RNA 2100) project, focusing on the water and agriculture sectors, which face a major challenge in Portugal. This challenge concerns present times and as shown here is expected to be greatly enhanced if society fails on delivering hard mitigation policies.

The Iberian Peninsula, as many other regions, is highly dependent on rainfed water systems and agriculture for which drought impacts can take large tolls on water supply and crop productivity (Guerreiro et al. 2017; Ribeiro et al. 2019a, 2019b; Bento et al. 2021). The projected changes throughout the century for all RCPs will certainly impact in the future ability of supplying water for all sectors and especially for agricultural production and, consequently threatening water and food security. This is utterly important in this war times, which are having global impacts on food production. Nonetheless, it is important to note that these impacts have significant spatial differences and future adaptation measures should be tailored to specific regional needs. Hence, the results of this study highlight the importance of developing adaptation strategies according to the different sectors and the different emission scenarios.

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