IMPACT OF CLIMATE CHANGE ON DROUGHT IN ARAGON (NE SPAIN)

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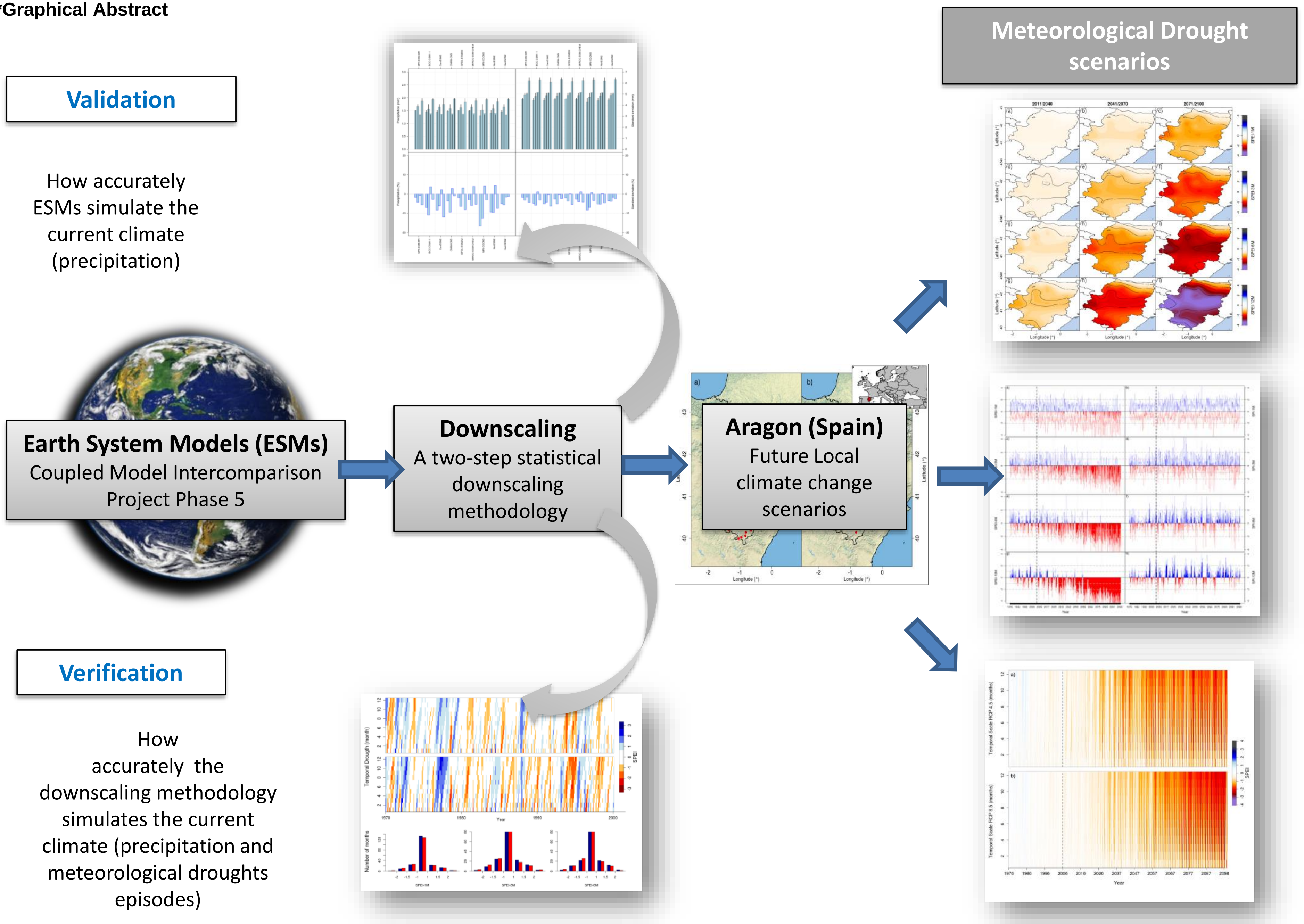
*Graphical Abstract



***Highlights (for review : 3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Highlights:

- Future SPI and SPEI scenarios for Aragon (Spain) were downscaled.
- Scenarios were based on the most recent Earth System Models (CMPI5) at first time
- The SPI, considering only precipitation, shows no changes in the water balance.
- The SPEI, considering the global warming, shows an increase of the drought episodes
- Hydroclimatic conditions of Aragon will change towards a drier climate

Abstract

Droughts are one of the extreme climatic phenomena with the greatest and most persistent impact on health, economic activities and ecosystems and are poorly understood due to their complexity. The exacerbation of global warming throughout this century probably will cause an increase in droughts, so accurate studies of future projections at a local level, not done so far, are essential.

Climate change scenarios of drought indexes for the region of Aragon (Spain) based on nine Earth System Models (ESMs) and two Representative Concentration Pathways (RCPs) corresponding to the fifth phase of the Coupled Model Intercomparison Project (CMIP5) have been generated for the first time. Meteorological Drought episodes were analysed from three main aspects: magnitude (index values), duration and spatial extent. The evolution of drought is also represented in a novel way, allowing identification, simultaneously, of the intensity of the episodes as well as their duration in different periods of accumulation and, for the first time, at the observatory level.

Future meteorological drought scenarios based on the Standardized Precipitation Index (SPI) hardly show variations in water balance with respect to normal values. However, the Standardized Precipitation Evapotranspiration Index (SPEI) which, in addition to precipitation, considers evapotranspiration, shows a clear trend towards increasingly intense periods of drought, especially when considering cumulative periods and those at the end of the century.

Representation of the territory of the drought indexes reflects that the most populated areas (Ebro Valley and SW of the region), will suffer the longest and most intense drought episodes. These results are key in the development of specific measures for adapting to climate change.

1. Introduction

Drought is probably one of the extreme climatic phenomena with the greatest impact on the world's population and that can affect millions of people every year around the planet (Bryant, 1991; Wilhite, 2000). It also has serious effects on the availability of water and therefore on economic activities such as agriculture (Lesk et al., 2016) and tourism and profound impacts on human health (Stanke et al., 2013) and ecosystems (Alary et al., 2014) that may persist over time. (Dai, 2011). However, drought is a phenomenon that is not well understood due to its complexity and lack of historical records (Wilhite, 2000) and because it depends on numerous factors.

For this reason, the scientific community and institutions are putting a lot of effort into understanding, identifying, documenting and monitoring this phenomenon more exhaustively. Examples are the drought databases of the European Drought Observatory, the National Drought Mitigation Center and, the historical database of the Standardized Precipitation Evapotranspiration Index (SPEI) (http://spei.csic.es/database.html).

1.1 Droughts types and indexes

Precipitation is the primary controlling factor of drought but other meteorological phenomena, such as temperature (Cook et al., 2014; Hao et al., 2017; Livneh and Hoerling, 2016), wind (McVicar et al., 2012a) and relative humidity (Willett et al., 2014), can modulate its intensity (Bates et al., 2008). Through potential evapotranspiration (PET), it is possible to evaluate the amount of water that would evaporate and transpire if there was enough water available, which is very important in the evaluation of meteorological droughts.

Because drought affects so many different aspects (environmental, economic, social, health), a single 'drought' does not really exist. Drought is often classified into four types (Wilhite, 2000; Wilhite et al.,1985): meteorological, agricultural, hydrological and socioeconomic drought.

The main subject of the current study is meteorological drought, a type of drought characterized by below-normal precipitation over a period of months to years and that should be defined as a condition relative to the normal local condition (Dai, 2011; Paparrizos et al.,2018; Wilhite, 2000).

On the other hand, to characterize droughts, standardized drought indexes are used in the literature. These indexes are direct indicators based on climate information, defined so that the results are comparable in time and space since droughts of the same magnitude can have very different effects depending on the time of year and the place where they occur (Hayes et al., 1999; Vicente-Serrano, 2016; Wilhite, 2000).

Some of these indexes are well established and have been used to monitor climatic conditions across different locations; these include the Palmer Drought Severity Index (PDSI; Palmer, 1965) and Standardized Precipitation Index (SPI; McKee et al., 1993), for example. The Lincoln Declaration on Drought Indexes (Hayes et al., 2011) determined that SPI is the only index, from the point of view of meteorological drought, valid for any region of the world and any time scale, being one of the most used in Europe (Spinoni et al., 2015). It is able to provide better spatial standardization than PDSI (Lloyd-Hughes and Saunders, 2002) and indicate drought initiation and termination because they are implicit parts of the index (Sonmez et al., 2005).

SPI, however, presents some limitations such as that it neglects the effect of temperature increase and, therefore, the effect that an increase in PET (Vicente-Serrano et al., 2010a) or in the atmospheric evaporative demand (AED) (Vicente-Serrano et al, 2020) can have on droughts, which may affect prediction of the impact of global warming in future drought conditions. It should be noted, however, that other meteorological variables as wind speed, solar radiation and air humidity, can also affect PET changes linked to climate change.

To avoid this problem, (Vicente-Serrano et al., 2010a) proposed a new climatic drought index, SPEI, which considers the difference between monthly precipitation and AED. Thus, SPEI best reflects climate change as it makes a more realistic measurement of water availability by incorporating the effect of temperature on changes in evaporation demand as does PDSI. On the other hand, it maintains the multi-temporal nature and simplicity of SPI (Marcos-Garcia et al., 2017).

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2014a), analysis of the precipitation regime (Calbo, 2010; Lavaysse et al., 2012), droughts (Burke and Brown, 2008; Lopez-Bustins et al., 2013) and the extreme temperatures that drastically increase evapotranspiration (ET) (Rebetez et al., 2006) and decrease soil moisture (Sheffield and Wood, 2008) suggest that drought episodes could become more severe around the world in the 21st century (Dai, 2013).

There are some studies that emphasize that future projections of drought may overestimate drought episodes if future soil moisture (Berg et al., 2017) and runoff (Yang et al., 2018) simulations are not taken into account (Berg and Sheffield, 2018), which can affect AED. In addition, recent studies highlight the need to include CO_2 concentration in the analysis of AED under climate conditions since an increase of the CO_2 acts contributing to the increase in temperatures that in turn affect the Vapour-Pressure Deficit (VPD). On the other hand, CO_2 could increase water use efficiency by plants reducing AED and therefore mitigate the drying (Dai et al., 2018; Roderick et al., 2015).

In this context, most European areas and the Mediterranean region seem to be prominent regional climate change hotspots where an increment in the occurrence of extreme events is expected (Beniston et al., 2007; Skaugen et al., 2004). Specifically, a possible rise in the intensity and frequency of extreme drought events is expected (Forzieri et al., 2014; Hoerling et al., 2012; Iglesias et al., 2007; Marcos-Garcia et al., 2017; Paparrizos et al., 2018), especially in the summer months (Vicente-Serrano et al., 2010c), and will have significant environmental, social and economic impacts (Blenkinsop and Fowler, 2007).

The global climate models used today reproduce temperature trends very well, but the level of precision for large-scale precipitation patterns is lower than for temperature

(IPCC, 2014b). This has caused the climatic projections of droughts to show great uncertainty and therefore we cannot know with precision the effects of climatic change on drought severity at the regional level in the future (Burke and Brown, 2008). This is especially problematic in areas with high precipitation variability, such as the Mediterranean region, where the drought patterns derived from the results of global climate models are not consistent (Vicente-Serrano et al., 2004).

1.2 Drought in NE Spain (Aragón)

In Spain, as in the rest of Europe (Feyen and Dankers, 2009), different series of major droughts have been happening in recent decades. In addition, the literature seems to indicate a trend towards an increase in meteorological water scarcity in the Iberian Peninsula, either due to an increase in the frequency of drought episodes or due to a change in the precipitation regime (Fragoso et al., 2018; Gallego et al., 2011; Garcia-Barron et al., 2011; Machado et al., 2011; Ojeda et al., 2017; Vicente-Serrano et al., 2004). This makes necessary studies at a local level and the development of future scenarios of droughts which are adequate as possible for evaluating the local impacts of climate change.

Drought scenarios in Spain are also scarce: either they are from studies conducted prior to the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC5) and in very small areas (Lopez-Bustins et al., 2013) or they use IPCC5 models but use dynamic downscaling information from the European Coordinated Regional Downscaling Experiment (EUROCORDEX; (Collados-Lara et al., 2018; Marcos-Garcia et al., 2017). The latter also evaluates only SPI and SPEI at the 12-month scale. However, these studies agree that the combined use of SPI and SPEI is adequate for studying drought episodes in the future (Lopez-Bustins et al., 2013; Marcos-Garcia et al., 2017).

The combined study of both indexes, SPEI and SPI could be an effective formula for an adequate study of meteorological drought in territories with the climatology of Aragon (NE Iberian Peninsula). This region of Spain is characterized by a continental

Mediterranean climate with high precipitation variability and marked by very diverse orography throughout its territory that includes areas of high mountains, valleys and steppes (López et al., 2007). In addition, we must consider that previous studies in Aragon have shown that an increase in temperature is one of the variables that will be most noticeable with climate change throughout this century (Gaitan et al., 2019; Ribalaygua et al., 2013a).

As far as we know, drought scenarios in Aragon have not been obtained to date. As has been seen, it is essential to have local scenarios to determine the impact of climate change on the environmental or socioeconomic reality of each region in order to make decisions on adaptation to climate change.

The goal of this study is to obtain, for the first time, meteorological drought scenarios for Aragon (located in NE of Spain) for the 21st century using a statistical methodology to downscale GCMs from CMIP5.

To achieve this goal, the capacity of the GCMs to simulate the past observed climate was assessed (validation) and using CMIP5, precipitation scenarios for Aragon were generated to simulate future daily precipitation.

Finally, as Aragon is a region sensitive to episodes of drought caused by a varying rate of precipitation and high temperatures, the SPI and SPEI meteorological indexes were calculated and the frequency of occurrence of drought and its spatial distribution were simulated to identify the drought vulnerability of the study area. Drought indexes were also verified.

This study provides, for the first time, scenarios of meteorological drought in the NE of Spain according to CMIP5 models, useful for predicting the impacts of climate change on the availability of water at a local scale and which are necessary for stakeholders to make decisions on adaptation and mitigation of climate change. On the other hand, this region of Spain is a good indicator of many characteristic areas of southern Europe (high mountains, river basins, steppes, etc.).

2. Data and methodology

2.1. Study area

The present study was carried out in the region of Aragon (NE of Spain) (Fig. 1). Because of its location, Aragon falls within the Western Mediterranean climate area characterized by scarce precipitation with cool winters and hot, dry summers. Differences in latitude between the most northern and most southern points of Aragon (340 km length and 240 km width) along with the influence of the Cantabrian and Mediterranean Seas and the general atmospheric circulation as well as the orographic complexity of the region (extreme altitude differences of over 3000 m between the plains (the Ebro River valley) and the mountains (the Pyrenees)), give rise to great subclimate variety, with different thermal and pluviometric regimes that condition the local climate (López et al., 2007).

Precipitation is scarce in most of Aragon and is distributed clearly according to relief, as the isohyets are arranged in concentric circles decreasing from mountain areas to the centre of the region. Although the average annual total precipitation of the Aragonese territory is around 550 mm, there are regions for which the average is below these values (for example, in the central sector of the Ebro Depression). Only in the Pyrenees and, to a lesser extent, in the Iberian Mountain Range, does precipitation reach important values, 1800–2000 mm, and show positive water balance values (considering the difference between precipitation and AED). On the other hand, more than 60% of the region has average values of AED above 1100 mm, showing a negative water balance, to which contributes not only the scarce rainfall but also the strong wind ("Cierzo") characteristic of the Ebro Valley (López et al., 2007). Therefore, 70% of the Aragonese territory is considered semi-arid (index value proposed by the United Nations Environment Program < 0.5 and even 30% presents values of 0.3) (Cherlet et al., 2018).

2.2. Datasets

2.2.1. Surface observation datasets

In this study, an observational dataset (daily maximum and minimum temperature and precipitation) belonging to the extensive network of instrumental observatories owned by the Spanish Meteorological Agency (AEMET) (http://www.aemet.es) was used (Fig. 1). This dataset is the same as the one used in previous studies (Gaitan et al., 2019; Ribalaygua et al., 2013a) in order to work with a set of data that has been subjected to strict quality control (inhomogeneities, gaps, outliers, transcription errors and so on) carried out first by the Government of Aragon (López et al., 2007) and completed, in a second phase, by (Ribalaygua et al., 2013a). As a complement to quality controls, those stations with a large number of data gaps or less than 15 years of daily records were discarded.

For the simulation of future climate scenarios of precipitation, a first set of 263 stations was used (red dots in Fig. 1a). Of these 263 stations, just those with data for both variables, temperature and precipitation, were used for the simulation of drought indexes (43 stations, Fig. 1b).

2.2.2. Atmospheric dataset

A set of nine climate models were selected from CMIP5, supplied by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archives.

The global climate models called Earth System Models (ESMs) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Tripathi et al., 2006) have contributed to the acquisition of both dynamic and statistical downscaling techniques with less uncertainty. These models integrate the individual parts of the climate system (atmosphere, ocean, land and sea ice) and the exchange of energy and mass between them (Knutti and Sedlacek, 2013). These models also include chemical processes, land use, plant and ocean ecology and an interactive carbon cycle, which enables integration of biochemical processes into the models (Heavens et al., 2013), constituting a robust set of coordinated climate model experiments (Carvalho et al., 2017; Chen et al., 2016; Perez et al., 2014).

The climate models (Table 1) were selected according to the time resolution (daily) of available predictor fields, because it is required for the downscaling method used. All of the models were ESMs (Jones et al., 2011; Wang et al., 2009).

This study used data from two different experiment families of GCMs: the Historical experiment (Taylor et al., 2012), which covers much of the industrial period and can be referred to as ‘twentieth-century’ simulations, and the Representative Concentration Pathway (RCP) family (Moss et al., 2010), which corresponds to different possible ranges of radiative forcing reached in the year 2100 with respect to values of the pre-industrial era. This study used future projections determined by the RCP8.5 ‘high’ scenario and RCP4.5 ‘intermediate’ scenario, the core of IPCC5 experiments.

In order to study the behaviour of the CMIP5 model Historical simulations, we used the reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF ERA-40; http://www.ecmwf.int/research/era/do/get/) (Uppala et al., 2005) for the period 1958–2000 at 6-hourly time resolution and 125 km spatial resolution. For verification of the methodology, it was necessary to reduce the temporal and spatial scale of the reanalysis in order to compare both ERA-40 and the climate model simulations (Ribalaygua et al., 2013a; Ribalaygua et al., 2013b). The geographical limits of the atmospheric window used were latitudes 31.5°N to 55.1°N and longitudes 27.0°W to 14.6°E, covering not only the geographic area under study but also the surrounding atmosphere areas which exert a meteorological influence all over the Iberian Peninsula (Ribalaygua et al., 2013a). The use of the ERA-40 data set has allowed us to compare these new results with those published by Ribalaygua et al 2013a.

2.3. Methodologies

2.3.1. Validation and generation of future precipitation scenarios

A two-step analogue/regression statistical downscaling method developed previously (Ribalaygua et al., 2013b) was applied to obtain future scenarios of precipitation and drought. This method has been used in national and international projects, with good verification results (Gaitan et al., 2019; Monjo et al., 2016; Moutahir et al., 2017; Ribalaygua et al., 2018; Rodriguez et al., 2014; Santiago et al., 2017). This methodology offers some advantages: it is computationally inexpensive, provides local information and allows quantifying the uncertainty associated with the downscaling process (Van der Linden and Mitchell, 2009). Other advantages are the application of future simulations consistent with observations (physically coherent between them) and using local scale (because nearby data points in space are not subjected to different climate change conditions) (Ribalaygua et al., 2013b).

Through the validation process we can, on the one hand, evaluate the ability of each ESM to simulate the predictor fields (comparing the downscaled Historical experiment simulation for each model with the downscaled ERA-40 simulation for a common period, 1958–2000) and, on the other, quantify the uncertainties inherent to future climate projections through an ensemble strategy (Monjo et al., 2016).

Bias and standard deviation at seasonal scale have been used as error measures. This validation process presents some limitations related to the observational data available to be considered in the final uncertainty analysis. More information about the validation process can be consulted in (Ribalaygua et al., 2013b).

Future local climate scenarios at local and daily scale for precipitation were produced for nine ESMs (see Table 1) and two RCPs (RCP4.5 and RCP8.5) as a previous step to calculate the drought indices. As precipitation is an essential variable in the analysis of drought, these scenarios are a starting point providing initial information on future pluviometric conditions.

The local climatic projections of precipitation belonging to CMIP5 were obtained in this study using the same methodology as that used for temperature scenarios, previously described (Gaitan et al., 2019).

2.3.2. Drought indexes

SPI was developed by McKee et al. (1993) and is based on two assumptions: 1) that the variability of precipitation is greater than that of temperature and AED, and 2) that the rest of the variables are stationary over time. The SPI value is defined as a numerical value that represents the number of standard deviations of precipitation, over the accumulation period in question, with respect to the average, once the original distribution of precipitation has been transformed into a normal distribution (i.e., mean of zero and standard deviation of 1). The SPI values can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean.

SPEI developed by (Vicente-Serrano et al., 2010a) and revisited by (Begueria et al., 2014) is a variant of the widespread SPI; it has greater potential as a drought index since it considers the climate balance (through the difference between monthly precipitation and AED). SPEI values can be interpreted in the same way as SPI values (number of standard deviations by which the observed anomaly deviates from the long-term mean).

Both indexes were calculated using the R package 'SPEI' (Version 1.7). The SPI was calculated using Gamma distribution to fit the original precipitation series (Organization WMO, 2012) and the SPEI was calculated using log-logistic distribution (Vicente-Serrano et al., 2015; Vicente-Serrano and Beguería, 2016). The parameters of these distributions were obtained by the method of unbiased probabilistic weighted moments (Vicente-Serrano and Beguería, 2016). The scale of SPI and SPEI values used in the study can be seen in Table 2.

The period 1976-2005 was used as a reference period, which represents the last 30 years of the Historical period. Based on this reference period, both the SPI and the SPEI were calculated for the period 2006-2100. The choice of the reference period was made to evaluate the future hidroclimatic conditions of the region with respect to the average conditions of the last 30 years of the Historical experiment.

To obtain the AED values used in the calculation of SPEI, both the Hargreaves-Samani (1985) and Thornthwaite (1948), formulas have been used, denominated SPEI-Har and SPEI-Thor, respectively. These formulas were chosen to calculate AED because they are recommended within the SPEI package and they also depend only on temperature and precipitation, unlike other more complex methods such as the Penman–Monteith (Smith M et al.,1998) and Jensen–Haise methods (Jensen and Haise, 1963). Both methods only take into account the temperature, so it is assumed that the calculation of AED trends could have certain limitations (Irmak et al., 2012b; McVicar et al., 2012b; Sheffield et al., 2012). For a certain increase in the temperature, the change in the obtained result can be higher than the one really expected according a complete method like Penman-Monteith. Therefore, the role of AED on drought severity would be overestimate and this would have some effect on the drought indices obtained for future scenarios.

The way in which the indexes have been analysed follows the guidelines of the WMO (WMO, 2017) which recommends analysis of a drought episode from three main aspects – magnitude (index values), duration (alternation between positive and negative values) and spatial extent – and all these aspects configure the severity of the episode.

In order to assess the capacity of the downscaling methodology to simulate SPI and SPEI, we analysed the intensity and duration of the different drought episodes shown by both indexes, comparing the SPI and SPEI values calculated from the simulated ERA-40 temperature and precipitation series with those obtained from the observed series for a common period (1970-2000). Verification of the maximum and minimum temperature and precipitation can be seen in a previous study (Ribalaygua et al., 2013a). The statistical measures used in the verification processes were the bias, standard deviation and Pearson correlation. The statistical measures were calculated using R computing software (R Development Core Team, 2010).

From the ESM simulated temperature and precipitation series (nine ESMs and two RCPs), we determined the drought episodes that are expected in Aragon during the upcoming decades of the 21st century. The SPI and SPEI scenarios were compared to a historical period (1976–2005) to analyse the future changes with respect to the actual situation of these extreme events.

To draw future local climate scenario maps, we used Thin Plate Spline (TPS) regression from the R package 'fields' (Nychka et al., 2015).

3. Results

3.1. Validation and precipitation scenarios

The results of the validation process (comparison between the ERA-40 precipitation simulations and the historical precipitation simulations for each ESM for a common period (1958–2000)) are shown in Fig. 2, for both absolute (mm) and relative precipitation (%). The results are variable depending on the model and the seasonal period; however, all the models are able to reproduce the annual cycle of precipitation as well as the differences between seasonal periods (maximum values in autumn and spring, followed by winter and summer). The obtained bias and standard deviation are less than ± 1 mm/day, which in relative terms supposes a difference of less than or around ± 10% in the worst of the cases.

In general terms, a big variation in the Aragon precipitation regime is not expected. According to scenario RCP8.5, mean variations in the amount of precipitation are expected to be around ± 10% for all seasons of the year, except for the summer where no precipitation change is expected. Scenario RCP4.5 shows no precipitation fluctuations throughout the 21st century with respect to current values (see support information, Fig. S1 to S4.

3.2. Generation of future local climate scenarios of drought indexes

3.2.1. Verification of drought index simulation

To verify the simulation of drought indexes, the first step was to compare the SPI and SPEI values obtained from the observations with those calculated from the simulated series of ERA-40.

Fig. 3 shows the verification results corresponding to SPI at time scales from 1 month (SPI-1M) to 12 months (SPI-12M) for the period 1970–2000 (Fig. 3a and 3b). This process allows the identification of episodes of deficit or excess precipitation recorded and simulated from ERA-40. In addition, the number of months in the period 1970–2000 in which SPI values were obtained within different intensity ranges (Table 1) for SPI-1M, SPI-3M and SPI-6M are shown (Fig. 3c, 3d and 3e).

As can be seen in Fig. 3a and 3b, the time series of the simulated SPI for ERA-40 shows, in an acceptable way, the same values presented by the observed SPI, with a correlation of $p = 0.75$ in the case of SPI-1M, $p= 0.72$ for SPI- 3M, $p = 0.64$ for SPI-6M and $p = 0.61$ for SPI-12M.

The simulated and observed SPI values show dry episodes (negative SPI) in similar periods, for example the periods 1970–1972, 1978, 1981–1982, 1989, 1994–1995 and 1998. The same can be seen for wet episodes (positive SPI) as in, for example, the periods 1976–1977, 1988 and 1996–1997.

Figs. 4 and S5 show the results of the verification process for SPEI based on SPEI-Har and SPEI-Thor calculations, respectively.

Similar results were obtained for calculation of SPEI based on the Hargreaves method (Fig. 4a and 4b) although in this case the correlation obtained between the observed and simulated time series of SPEI is slightly higher (0.80 for SPEI-1M, 0.78 for SPEI-3M, 0.72 for SPEI-6M and 0.73 for SPEI-12M).

When the Thornthwaite method is used for calculating AED in SPEI (see Fig. S5), the temporal correlations are lower than those obtained with SPEI based on Hargreaves.

On the other hand, for about 65–70% of the period considered, water balance conditions in Aragon was considered normal (SPI/SPEI between −0,5 and 0,5), suffering extreme wet or dry episodes for only 2–4% of the period 1970–2000.

The error (bias) made in the simulation of SPI (Fig. 3c to 3e) and SPEI (Fig. 4c to 4e) is quite small for all of the classes considered (< ± 2 months).

3.2.2. Local climate scenarios to predict drought indexes

Figs. 5 to 9 (complemented with Figs. S6 and S7) show the results obtained for the simulation of SPI and SPEI throughout the 21st century from different perspectives.

Fig. 5 shows local climate change scenarios for future SPEI (a, c and d) and SPI (b, d and f) at 3-, 6- and 12-month scale, which have been predicted on the basis of the nine models (see Table 2) and here are used to obtain a general vision of the changes in water balance for the Aragon region as a whole. The future projections of SPI and SPEI for the period 2006-2100 have been made based on the reference period (Historical 1976-2005). When working with normalized indexes, the future values of the SPI and SPEI represent anomalies with respect to the average values of the reference period, which allows to evaluate the future evolution of the hydric conditions in Aragon with respect to the average of the last 30 years of the Historical experiment.

The SPI values obtained are hardly modified with respect to the Historical period so, according to these results, the water balance characteristics of the region as a whole would remain similar to the current ones. On the other hand, the SPEI climate change scenarios, considering the effect of AED, show a marked tendency towards increasingly negative values of the index with respect to the Historical period, especially at the end of the century.

Both RCPs show a similar evolution until 2060, with changes of SPEI with respect to the Historical period of −0.6 for SPEI-3M, −0.9 for SPEI-6M and −1.3 for SPEI-12M. For the final period of the century, the variation begins to be more pronounced under the conditions of RCP8.5, with changes of −1.2 for SPEI-3M, −1.8 for SPEI-6M and −2.8 for SPEI-12M, while under scenario RCP4.5, SPEI values vary slightly from those reached in 2060.

These results are very well reflected in the time-scale evolution maps, where the simulated time series from 1976 to 2100 are represented, both for SPEI (Fig. 6) and SPI (Fig. 7) and under both scenarios, RCP4.5 (Figs. 6a and 7a) and RCP8.5 (Figs. 6b and 7b) with respect to different time scales (from 1 to 12 months).

Fig. 6 shows a tendency towards more and more extreme SPEI values, especially in the longer time scales. For time scales of up to 4 months, an alternation between periods considered normal and dry periods is expected (SPEI values between −1,5 and 0,5). For longer time scales, there is a tendency towards more intense and prolonged periods of drought, with SPEI values of up to −3 at the end of the century. The pattern obtained is similar under both RCPs, being more pronounced in the case of RCP8.5.

In the time-scale map corresponding to SPI (Fig. 7), the same pattern as that obtained for SPEI is not appreciated; in this case, alternating dry and wet periods are observed for all time scales, these being somewhat more extensive as we move along the time scales. The same pattern is observed under both RCPs, the signal being slightly stronger in the case of RCP8.5.

As a complement to the previous results, which allowed the extraction of results for the water regime of Aragon as a whole, the spatial maps of both indexes are shown. Figs. 8 and 9 show the climate scenarios for mean SPEI according to RCP4.5 and RCP8.5, respectively. These figures show the temporal evolution for four time scales: 1 month (first row), 3 months (second row), 6 months (third row) and 12 months (fourth row). The temporal periods chosen were 2011–2040 (present), 2041–2070 (mid-century) and 2071–2100 (end-century). Figs. S6 and S7 show the same information but for mean SPI.

The results for SPEI vary considerably between different points in the Aragon region. Coinciding with what was said before, it is observed how the SPEI values become more extreme as the 21st century and time scales advance. The Ebro Valley area is the one that will be subject to more intense episodes of precipitation shortage at the end of the 21st century, with SPEI values from −1 at 3 months to −2 at 12 months according to RCP4.5 and considerably more intense under RCP8.5 with values from −1.8 at 3 months to −4 at 12 months. The north-west area of the region, which is expected to be most affected by drought episodes, deserves special attention. The Pyrenees zone is the one that will clearly suffer the fewest expected drought episodes;

under RCP4.5 it is expected to remain in normal water balance conditions while under RCP8.5, at most, SPEI will reach values of −1.5 (at the end-century and at 12-month time scale).

The SPI spatial maps (Figs. S6 and S7) show how the region will remain under normal water balance conditions, highlighting the Ebro basin at the end of the 21st century and under RCP8.5, where more negative values of SPI (around −1) are appreciated, but which are still within the range considered normal for the region.

It is important to emphasize that if the average value of the SPEI/SPI tends to increasingly negative values and if this is a constant trend in the future, the conditions considered normal today will evolve towards new values considered normal (Vicente-Serrano et al. 2020).

This study has been carried out for each of the observatories used in the study and for each of the climatic models, which reveals that the entire region is going to be affected by episodes of drought despite its location and height. As an example, the temporal evolution of both indexes obtained according to the MPI-ESM-MR climate model and under both RCPs is shown for the observatories of Zaragoza (Figs. 10 and 11) and Cedrillas-Huesca (Figs. S8 and S9).

The choice of these observatories was based on the Climate Atlas of Aragon (López et al., 2007), since they are two of the reference points used in the climatic characterization of the region. The choice of these observatories was also made based on their location; the Zaragoza observatory is located in the Zaragoza airport station at a height of 263 m while the Cedrillas-Huesca observatory is located in the northern area of the region at a height of 1347 m. In addition, the Zaragoza airport station is considered representative of the variability of temperatures in Aragon (Roldan et al., 2011).

The expected temporal evolution of SPEI throughout the 21st century is consistent with that explained above, but as it is a single climatic model and uses a single observatory, the alternation between wet and dry periods can be seen more clearly at a time scale of 1 to 3 months. Also, as we move forward in the time scales, this alternation softens, resulting in periods of more intense and prolonged precipitation shortage while, for SPI, the alternation between wet and dry periods is observed for all time scales. This highlights, as for SPI, how periods with positive SPI for the Cedrillas-Huesca observatory are more intense and prolonged than those predicted for Zaragoza.

4. Discussion

These results offer the possibility of having future climate projections based on recently updated data, allowing the evaluation of how drought could affect the region of Aragon, both spatially and temporarily, and can be taken as a reference to analyse its impact on multiple sectors. Temporally, drought increases to the end of the century; at the territory level, the area most affected will be the central area of the Ebro Valley, where most of the population in the area is concentrated.

The difficulty of developing impact studies and quantifying their damage as a result of periods of water scarcity comes mainly from the lack of observed values and studies at a local level with future projections, hence the need to publish studies of these characteristics.

In this study, climate change scenarios of drought indexes for the region of Aragon, Spain, based on nine ESMs corresponding to CMIP5 have been generated for the first time.

The evolution of two indexes, SPI and SPEI, has been obtained throughout this century and also over the territory, which has allowed us to observe that while SPI, which only considers precipitation, shows few changes, SPEI, that considers temperature and incorporates the effects of AED, shows a tendency towards periods of increasingly intense drought, especially when considering accumulated periods of longer duration and those at the end of the century. Therefore, in the current climate change context it is essential to take into account the effect of temperature in the study of droughts.

Figs. 6 and 7 represent a novel representation of the evolution of drought, allowing identification, simultaneously, of the intensity of the episodes and their duration in different periods of accumulation.

One of the strengths of this study is the use of local climate scenarios (at the observatory level) to generate future drought indexes. Having this information will facilitate decision-making in the face of expected changes based on what is expected to occur at each observatory and not in the region a whole. As an example of the study at local level, the results of future climate scenarios for Zaragoza (representative observatory of Aragon, Roldan et al., 2011) and Cedrillas-Huesca (support information) are shown.

4.1. Precipitation scenarios used for the simulation of drought indexes.

For the simulation of precipitation, ESMs have been used instead of climatic models. ESMs are the most powerful climatic models to date and incorporate significant improvements (Flato et al., 2014) that allow better accuracy in climate simulation, as can be seen in the good results obtained in the validation process.

Validation of the ESMs has shown good results for simulating precipitation. Both the obtained bias and standard deviation are less than ± 1 mm/day, which in relative terms supposes differences of less than or around ± 10% in the worst cases; however, those values are within the order of natural variability of precipitation. These results are better than those obtained for the generation of scenarios of the fourth IPCC report published by (Ribalaygua et al., 2013a) particularly in the summer months, a particularly critical time in Aragon.

The results obtained for the processes of verification of the methodology (Ribalaygua et al., 2013a) and validation of the ESMs are good enough to allow the use of local climatic scenarios generated under these conditions in impact studies and analysis of extreme episodes such as periods of precipitation shortage.

Future precipitation scenarios show, under RCP8.5 conditions, a slight decrease in precipitation throughout the 21st century for all seasons of the year, except for the summer months where there is hardly any variation compared to current values of precipitation in the region. Under RCP4.5 conditions, less pessimistic than the previous one, barely any precipitation changes are expected at any time of the year.

These results are consistent with those published by AEMET (www.aemet.es) and directly by the IPCC (Mukherjee et al., 2018), although the latter show the direct outputs of the ESMs and do not carry the added value of applying downscaling techniques.

4.2. Consideration of the simulation of drought indexes

SPI is considered by experts in this field as one of the few indexes applicable in any region of the world for any time scale (Hayes et al., 2011) and with multiple advantages of application compared to other indexes of widespread use such as PDSI (Dracup et al., 1980; Guttman, 1998; Hayes et al., 2011; Hayes et al., 1999; Vicente-Serrano et al., 2010b). In the context of climate change with significant temperature variations (Gaitan et al., 2019), SPEI has been chosen; its formulation is similar to that of SPI and allows the comparison of both indexes and evaluation of the future behaviour of drought episodes considering the effects of future temperature changes. Both indexes have been verified and used previously in Aragon (Vicente-Serrano et al., 2010a). We have only used the temperature in the calculation of AED because the absence of observed historical data of variables such as radiation or humidity does not allow us a correct validation process of certain indices such as Penman that include these variables.

4.2.1. Verification results

In general, the results of the verification process show good correlations between the observed and simulated time series for both indexes for the period 1970–2000, higher ones being obtained for SPEI. This is consistent with the results published by Vicente-Serrano et al. (2012); they obtained higher correlations for the calculation of SPEI than SPI, especially for the summer months, which are the most critical in the region of Aragon.

The temporal series based on observations are satisfactorily represented by the temporal series based on simulations, recreating almost all dry and wet episodes of importance. It is observed how both the simulated SPI and SPEI tend, for the majority of times, to present dry and humid periods of greater intensity than those observed, especially for longer time scales, as occurred in 1976–1977 for positive values of the indexes and in 1981–1982 for negative ones. In general, the number of months of the period 1970–2000 located within each of the classes defined for SPI/SPEI has been simulated very satisfactorily.

The dry and wet periods detected in this study coincide with or are approximate to those published previously (Vicente-Serrano and Lopez-Moreno, 2005) based on SPI (dry episodes: 1986–1987, 1989 and 1994–1997; wet episodes: 1976–1980), in the Climate Atlas of Aragon (López et al.,2007) based on the precipitation regime (dry episodes: 1970, 1985, 1993 and 1995), by Spinoni (Spinoni et al., 2015) based on a combined 12-month index (dry episodes: 1979–1980 and 1995–1998) and by Tselepidaki (Tselepidaki et al., 1992) from a European study (dry episode: 1989), among others. In some cases, the years are not exactly the same because of the use of different drought and temporal scale indexes.

4.2.2. Future scenarios

The uncertainties associated with both processes, verification and validation, should be considered when interpreting future scenarios. For drought projections the focus should be on changes in the frequency and magnitude of cases located at the lower tail of the distribution as was recommended by Vicente-Serrano et al. (2019).

Future meteorological drought scenarios based on SPI barely show water balance variations with respect to normal values, regardless of the time scale considered and the region of Aragon, except for the Ebro Valley where there is a slight sign of drought at the end of the 21st century and under the conditions of RCP8.5.

These results were expected due to precipitation scenarios barely showing changes throughout the 21st century.

When considering other climatic variables, such as temperature, the drought scenarios based on SPEI show a clear trend towards increasingly dry periods and longer droughts, especially in the Ebro area and south-west of the region. According to the trends shown by the temperature and precipitation scenarios obtained for Aragon, the results obtained were expected. The fact that the results obtained at the 12-month scale are more intense than those of 1-3 months is partly a result of the way in which drought indices are formulated and the autoregressive component of its metric so that when the timescale increases, changes in the frequency of drought conditions increase more in comparison to changes in the mean state. Although, recently, Vicente-Serrano et al (2019) showed that these changes are independent of the metric with which these indices have been calculated, changes in the frequency of drought conditions increase more in comparison to changes in the mean state.

The lack of consideration of variables such as temperature, wind or humidity in the calculation of SPI means that this index presents certain limitations under global warming conditions(Mishra and Singh, 2010; Mishra and Singh, 2011; Vicente-Serrano et al., 2010a) and it is for this reason that, when considering AED in the calculation of SPEI, such different results are obtained, especially at the end of the century and not only under the conditions of RCP8.5, that some authors consider less realistic (Hausfather and Peters, 2020), but also of RCP4.5.

Some studies recommend the use of PET and add value against global warming (Hu and Willson, 2000; Vicente-Serrano et al., 2010a),Tsakiris and Vangelis, 2005). Recent studies (Vicente-Serrano et al. 2019; Vicente-Serrano et al., 2020) suggest using AED in the future study of droughts, as well as analyzing the impact caused by the increase in CO_2 (Yang et al., 2019). Probably, considering the response that vegetation could have to an increase in CO_2 and, therefore, in the evapotranspiration process, could provide some variation in the future evolution of drought episodes that should be explored in future studies.

The results of future drought scenarios presented here show results in line with those obtained in other studies where it is concluded that the Mediterranean regions will experience an increase in the severity and frequency of droughts (Stagge et al., 2015) as a result of a slight decrease in precipitation and an abrupt increase in temperatures (European Environment Agency, 2010; (Stagge et al., 2015) and which represent an increase in water scarcity (Estrela et al., 2012). More specifically in the region of Aragon, the ECCE project, based on dynamic downscaling and scenarios of the fourth IPCC report (Ministerio de Medio Ambiente, 2011), showed a future decline of the Ebro runoff, and Cook (Cook et al., 2014), based on scenarios of the fifth IPCC report but without downscaling, obtained an increase in drought episodes based on SPEI.

4.2.3. Impact on the territory

Although there have been studies on the Aragon area, none present as complete a picture as this study, combining drought evaluation with SPI and SPEI (that is, considering the effect of global warming) based on scenarios of the fifth IPCC report and providing the added value of working at the local scale by applying a downscaling technique.

The scenarios obtained in this study indicate that the Ebro Valley, the most populated area in the region that includes the largest city, Zaragoza with more than 650.000 people, will be most susceptible to future periods of extreme drought and will suffer periods of drought of greater intensity and duration, especially at the end of this century, which will have consequences in sectors such as health, water management, economy and society in general (Lee et al., 2017).

It is remarkable that, in previous publications (Ribalaygua et al., 2013a), we detected that the highest values of maximum temperature, especially at the end of the century and in summer (around 40 °C) as well as the greatest intensity of heatwaves will also take place in this area, so it will be especially vulnerable and these data should be considered in the development of specific measures for adapting to climate change.

Adaptation to climate change in each region requires studies applied to the climatic dynamics of each territory, so downscaling quality studies are essential for this. However, these results at the local level are also useful for the whole of the southern Iberian Peninsula and central Europe, since Aragon brings together geographical and climatic features representative also of these other areas.

5. Conclusions

The generation for the first time of climate change scenarios of drought indexes for the region of Aragon (Spain) based on nine ESMs and two RCPs from CMIP5 has allowed us to obtain simultaneously the most accurate representation to date of the magnitude, duration and intensity of meteorological drought episodes and their duration in different periods of accumulation in this area of Spain. The use of different drought indices and drought time-scales and its graphic representation is a relevant novelty in the scientific literature.

This has allowed the detection of a clear trend towards increasingly intense periods of drought, especially at the end of the century when cumulative periods of longer duration are considered. This trend is detected only in the future drought scenarios based on SPEI (which in addition to precipitation, considers AED), while in the SPI-based scenarios it is softened. These results reinforce the need to study these extreme phenomena in a context of climate change, considering the temperature.

At the territory level, spatial representation allowed us to discover that the area that will be most affected by longer and more intense periods of drought, but also the greatest decrease in precipitation (around 10%), is the Ebro Valley, the area that concentrates most of the population as well as the main economic activities of the zone. The results have also allowed, for the first time, the study of future drought indexes at the observatory level, specifically for the most populous city, Zaragoza.

To cope effectively with the impacts of these extreme events that are expected in the present century, it is essential to be able to generate local scenarios that accurately describe climate change at the territory level. On the one hand, our results not only confirm a trend already described in the Mediterranean area of an increase in the severity and frequency of droughts but can also serve as a model and sentinel for similar areas, since it has very varied climatic and orographic conditions.

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GFDL-ESM2M	2ºx2,5º daily	National Oceanic and Atmospheric Administration (NOAA), E.E.U.U.	Dunne et al. (2012)
CanESM2	2,8ºx2,8º daily	Canadian Centre for Climate Modeling and Analysis (CC-CMA), Canadá.	Chylek et al. (2011)
CNRM-CM5	1,4ºx1,4º daily	CNRM (Centre National de Recherches Meteorologiques), Meteo-France, Francia.	Voldoire et al. (2013)
BCC-CSM1-1	1,4ºx1,4º daily	Beijing Climate Center (BCC), China Meteorological Administration, China.	Xiao-Ge et al. (2013)
HADGEM2-CC	1,87ºx1,25º daily	Met Office Hadley Center, United Kingdom.	Collins et al. (2008)
MIROC-ESM-CHEM	2,8ºx2,8º daily	Japan Agency for marine-Earth Science and Technology (JAMSTEC), Atmosphere and Ocean Research Institute (AORI), and National Institute for Environmental Studies (NIES), Japan.	Watanabe et al. (2011)
MPI-ESM-MR	1,8ºx1,8º daily	Max-Planck Institute for Meteorology (MPI-M), Germany.	Raddatz et al. (2007); Marsland et al. (2003)
MRI-CGCM3	1,2ºx1,2º daily	Meteorological Research Institute (MRI), Japan.	Yukimoto et al. (2011)
NorESM1-M	2,5ºx1,9º daily	Norwegian Climate Centre (NCC), Norway.	Bentsen et al. (2012); Iversen et al. (2013)

Table 1. Information about the nine climate models belonged to the 5 Coupled Model Intercomparison Project (CMIP5) corresponding to the fifth report of the IPCC. Models were supplied by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) archives.

SPEI/SPI	
≥ 2	extremely wet
1.5 a 2	severely wet
0.5 a 1.5	moderately wet
-0.5 a 0.5	normal values
-1.5 ≤ -0.5	moderately dry
-1.5 ≤ -2	severely dry
≤ -2	extremely dry

Table 2. SPEI/SPI Intensities Scale (Vicente-Serrano et al 2010a)

Figure
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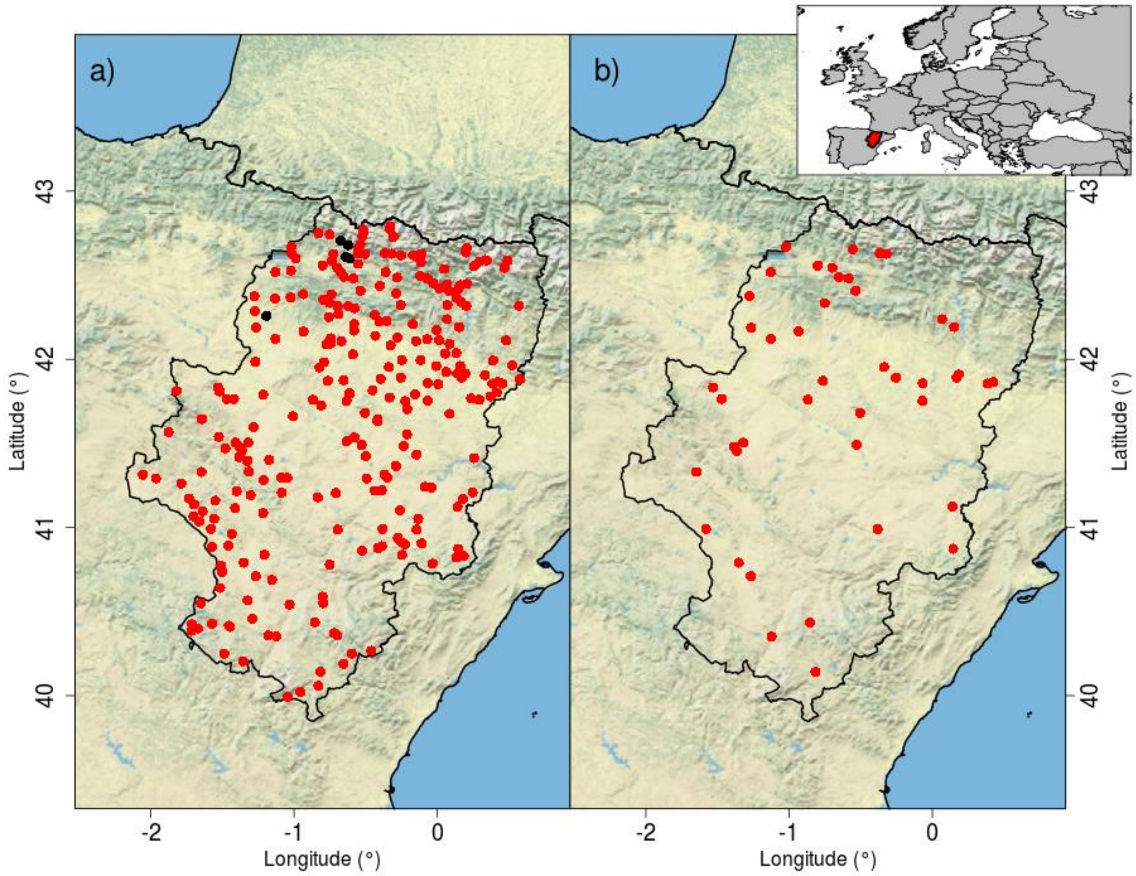

Figure 1. Location of the study Area and observatories. Aragon (Spain) in Europe. Points indicate the stations used in the study. a) Stations of precipitation (264) used in the generation of climate regional scenarios of precipitation (verification, validation and scenarios). b) Stations used exclusively on the generation of drought indexes (43). Map source: OpenStreetMap.

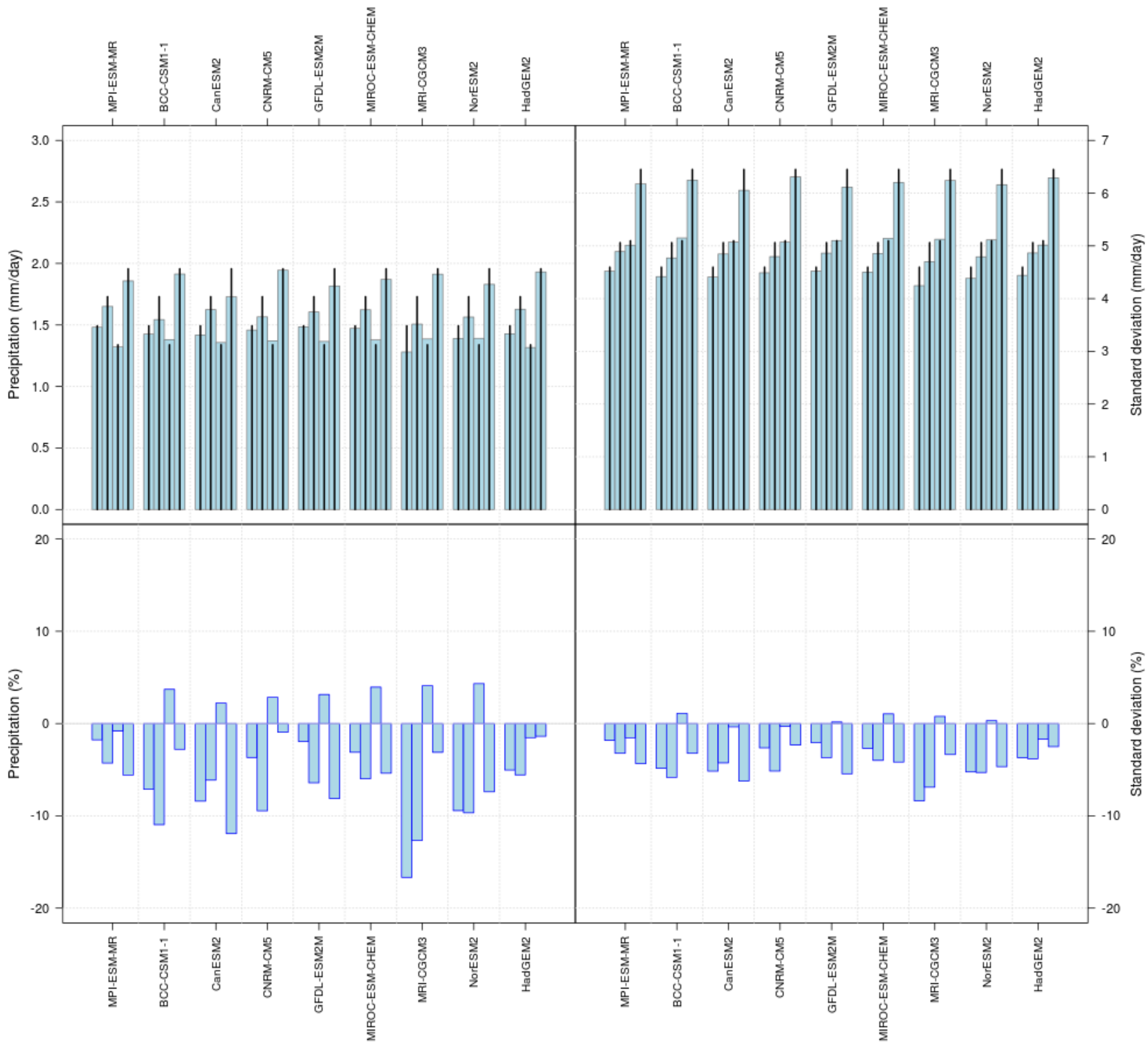

Figure 2. Validation of precipitation. Comparison between the precipitations obtained using the downscaled Historical data of the global climate models and the downscaled reanalysis data, for every seasonal period. Two graphs at the top: seasonal comparative between the precipitation simulated using the downscaled Historical data (colour bars) and that of the downscaled reanalysis data (black lines) for each global climate models (see Table 1) and for the four seasons: winter (December-February; first bar of each group of four), spring (March–May, second bar), summer (June–August; third bar) and autumn (September–November; four bar).

Two graphs at the bottom: relative seasonal differences between the simulated data using the downscaled Historical data and that of the downscaled reanalysis data.

Seasonal precipitation amounts are shown on the left columns and seasonal values of the standard deviation on the right columns.

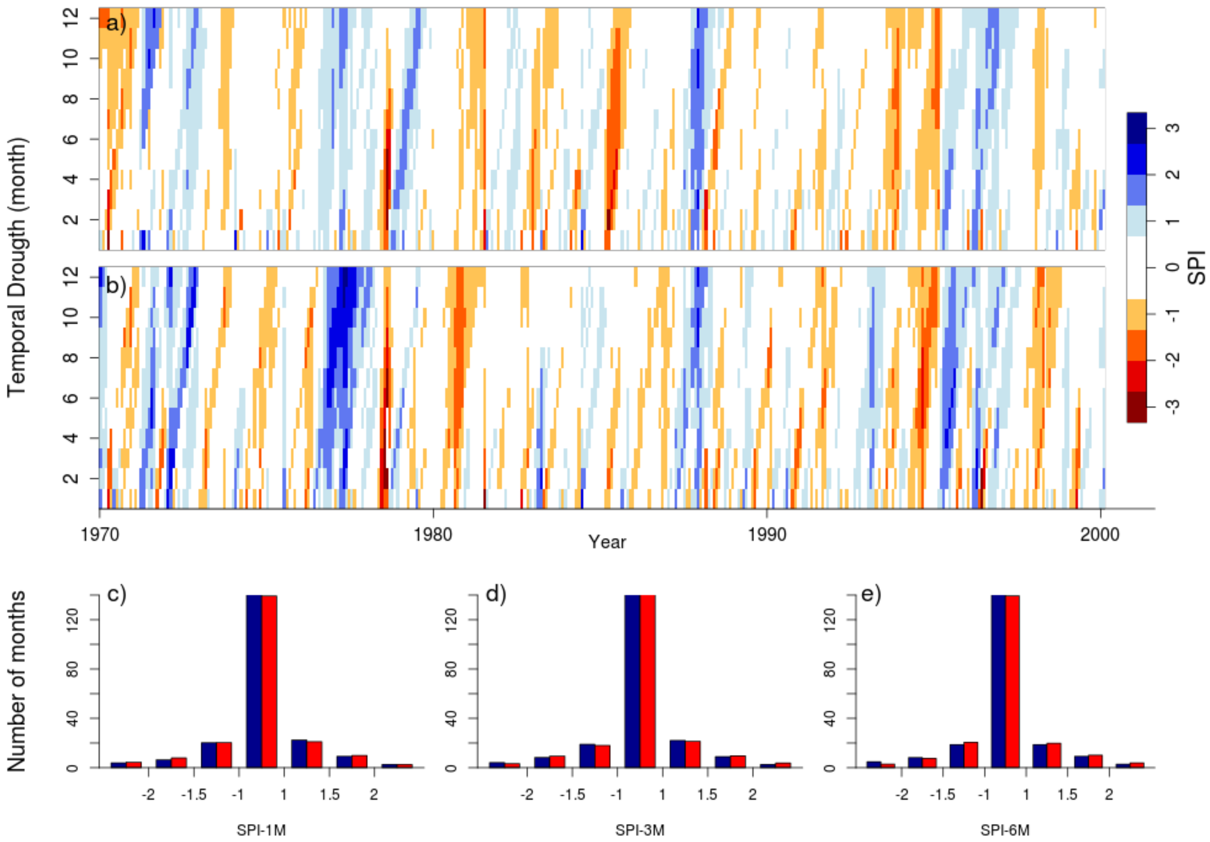

Figure 3. SPI verification. Results of the verification process for the SPI. a) time series of the SPI index calculated from observed data at the time-scales from 1 to 12 months for the period 1970-2000, b) time series of the SPI index calculated from downscaled ERA-40 at the time-scales from 1 to 12 months for the period 1970-2000. c), d) and e) number of months within the 1970-2000 period corresponding to each interval of the SPI intensities scale based on observed data (blue columns) and on downscaled ERA-40 (red columns) for the time-scales of 1, 3 and 6 months. Average of the all the stations used in the simulations.

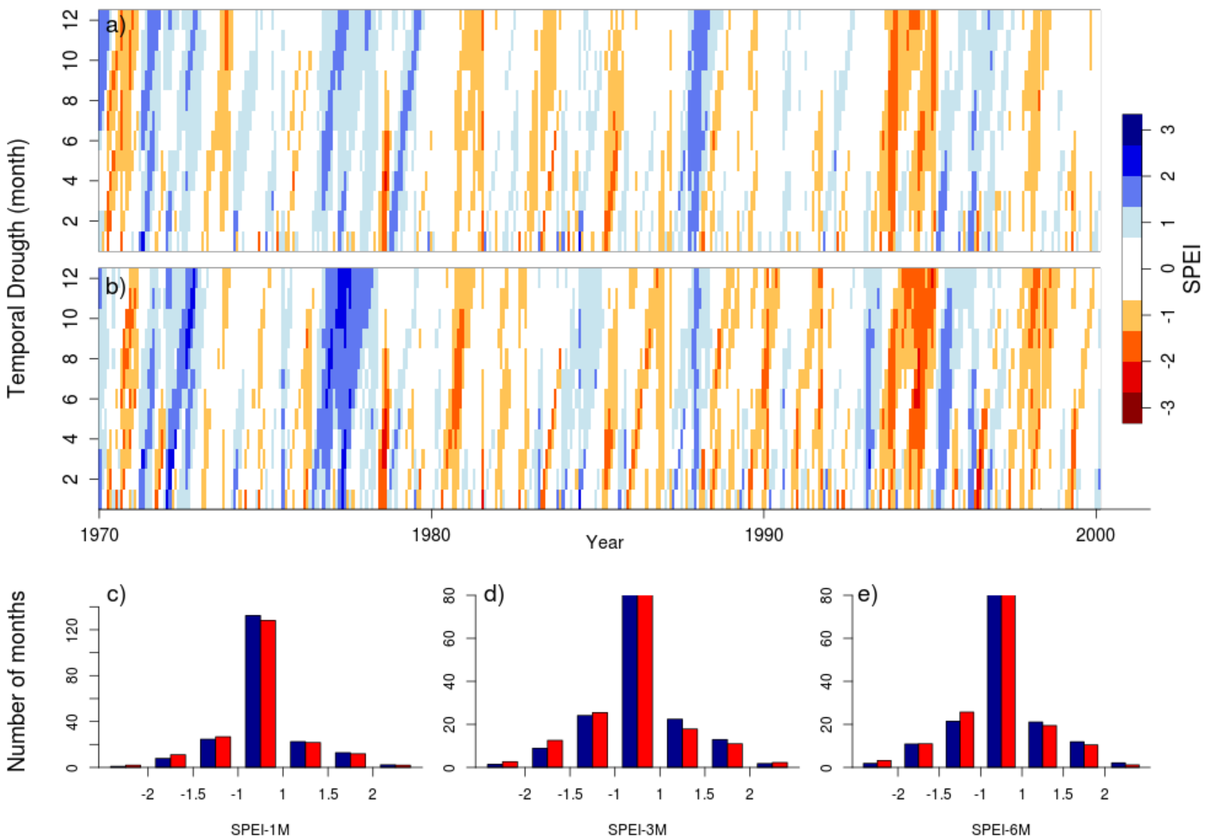

Figure 4. SPEI Har verification. Results of the verification process for the SPEI based on Hargraves Evapotranspiration. a) time series of the SPEI index calculated from observed data at the time-scales from 1 to 12 months for the period 1970-2000, b) time series of the SPEI index calculated from downscaled ERA-40 at the time-scales from 1 to 12 months for the period 1970-2000. c), d) and e) number of months within the 1970-2000 period corresponding to each interval of the SPI intensities scale based on observed data (blue columns) and on downscaled ERA-40 (red columns) for the time-scales of 1, 3 and 6 months. Average of the all the stations used in the simulations.

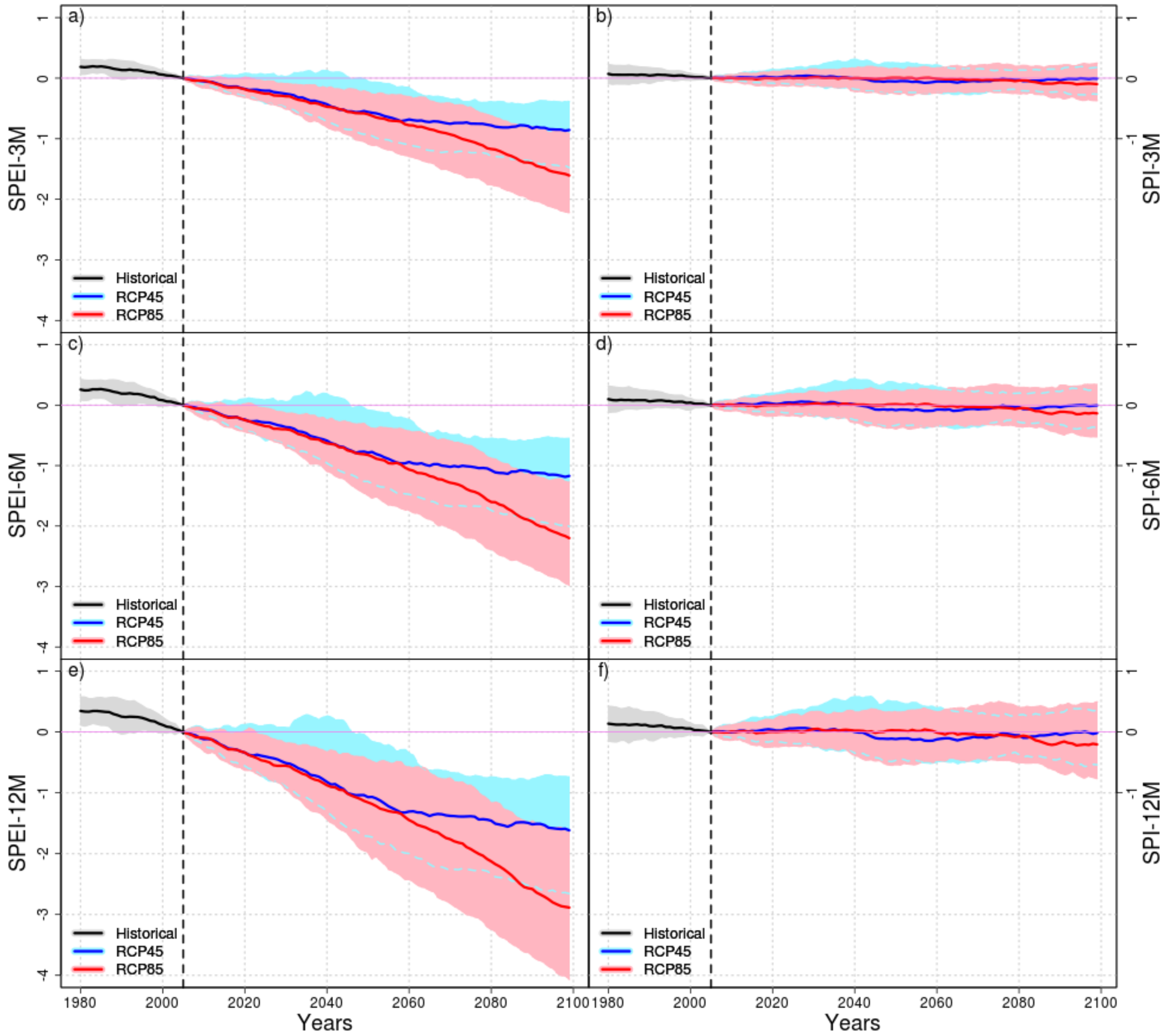

Figure 5. Simulated SPEI and SPI for the twenty-first century. Values are displayed as absolute increase compared to the amount simulated for the 1976–2005 Historical period for the time scales 3 months (a and b), 6 months (c and d) and 12 months (e and f). The vertical dotted line marks the end of the Historical data (2005). Data grouped for every RCP simulation of every global climate model selected and for the last 30 years of every station. The ensemble median (solid lines) and the 10th–90th percentile (shaded areas) values are displayed.

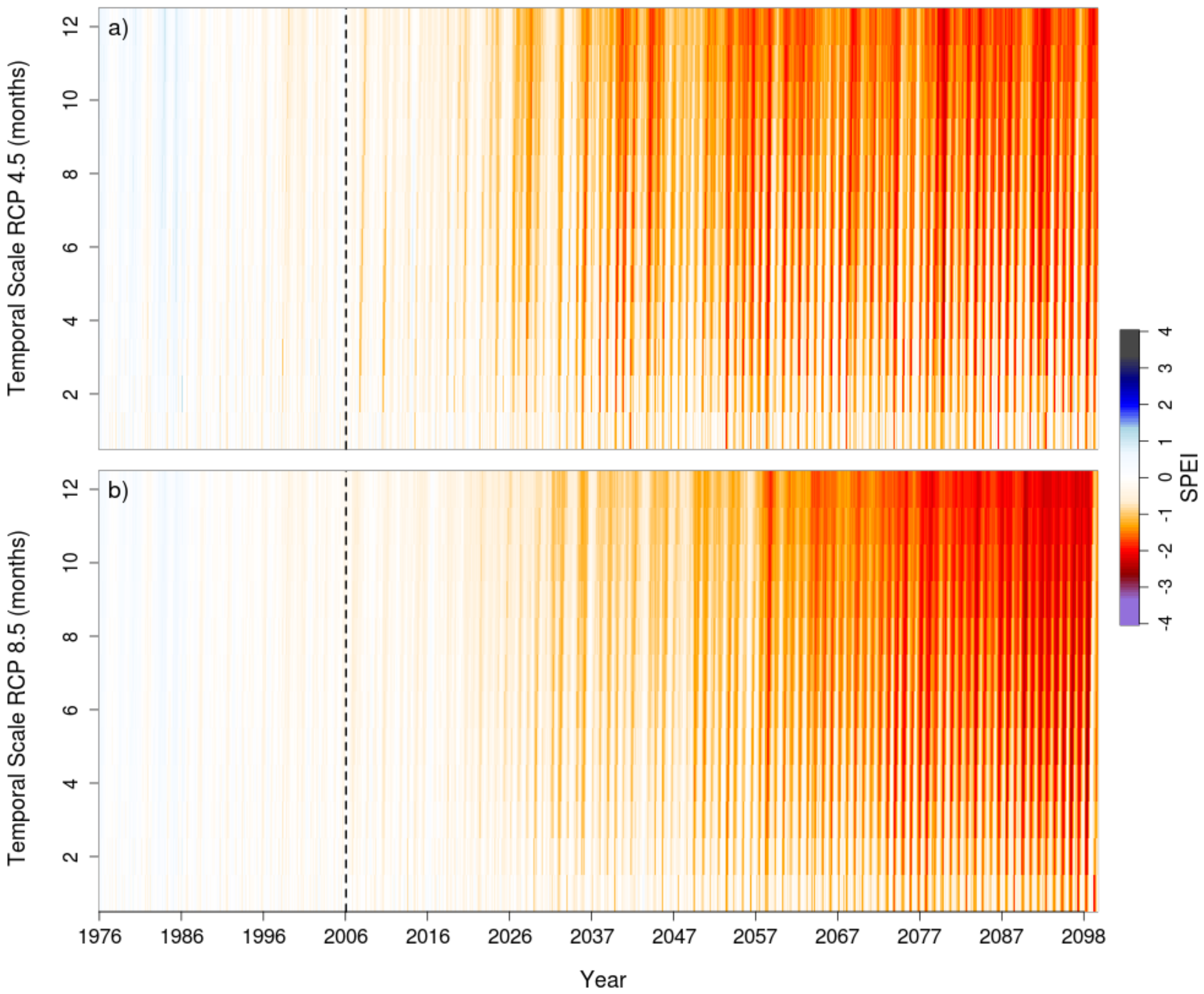

Figure 6. SPEI Time series under RCP4.5 and RCP8.5 along the 21st century at time-scales from 1 to 12 months. Data grouped for every RCP simulation of every global climate model and for every station. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b)

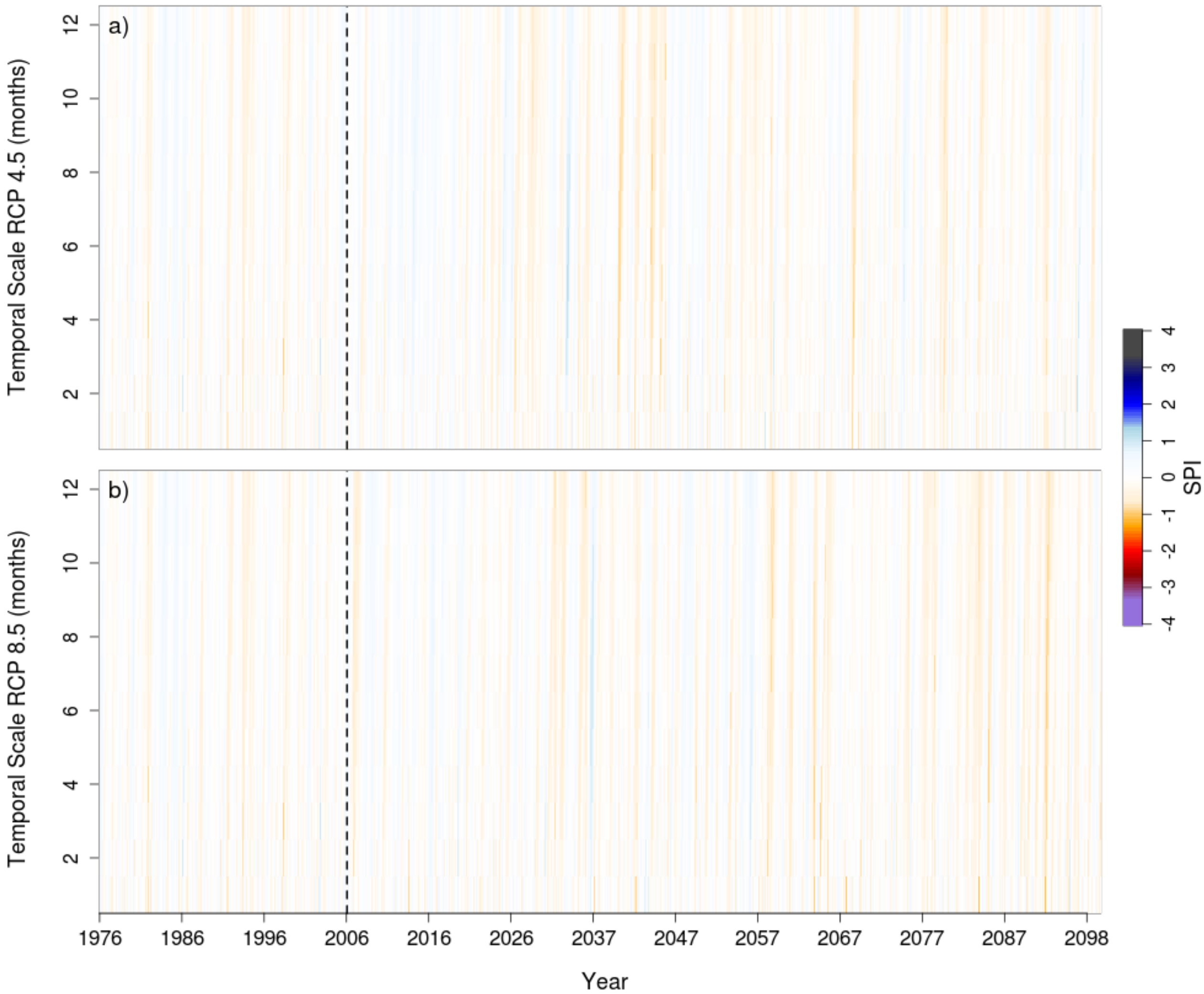

Figure 7. SPI Time series under RCP4.5 and RCP8.5 along the 21st century at time-scales from 1 to 12 months. Data grouped for every RCP simulation of every global climate model and for every station. Both emissions scenarios are represented: RCP4.5 (figure a) and RCP8.5 (figure b).

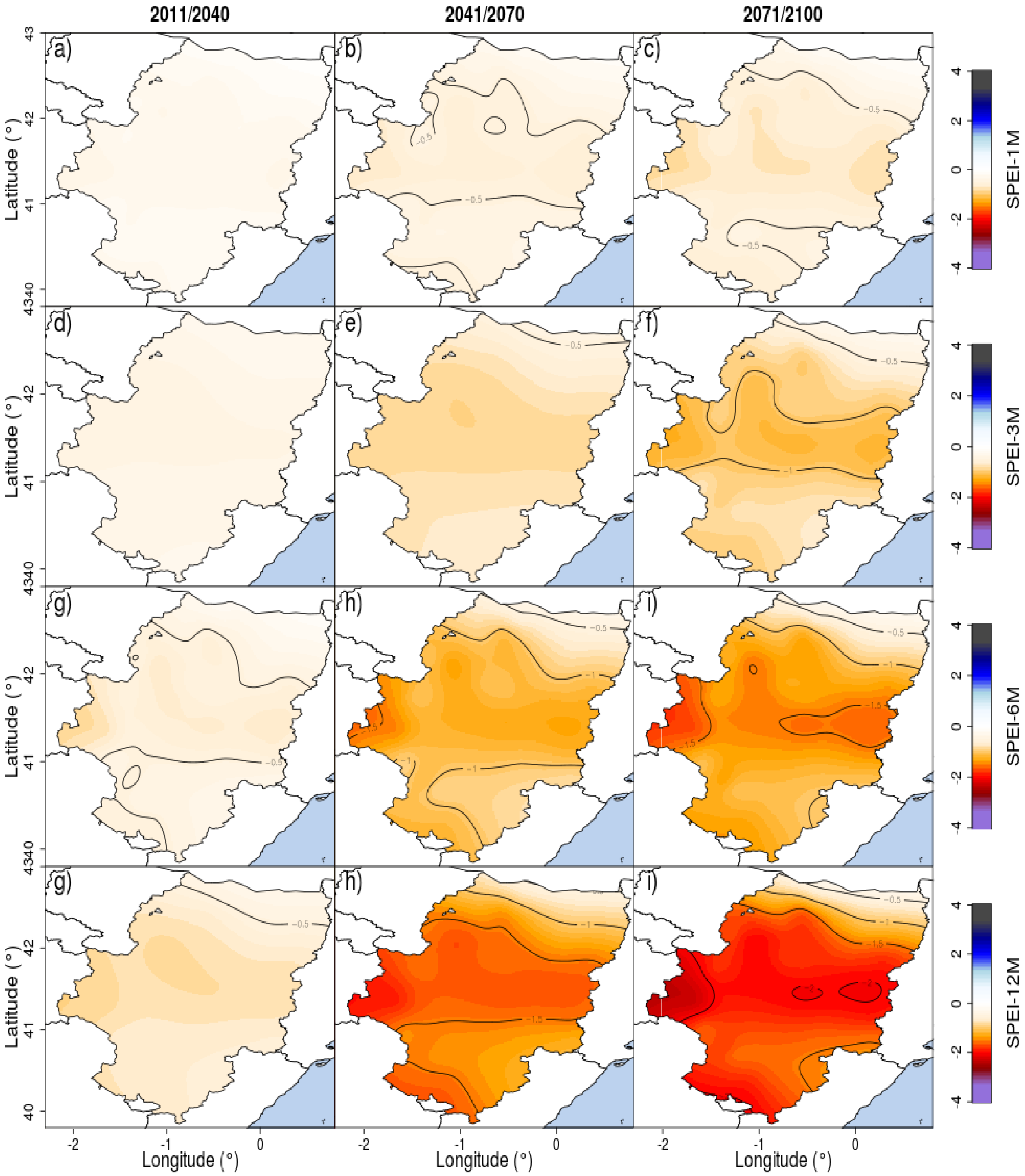

Figure 8. Time-scales SPEI maps under RCP4.5. Geographical representation of the expected evolution of the SPEI for Aragon in the periods 2041–2070 and 2071–2100 compared to the reference Historical Period (1971–2000) in terms of absolute values according to the RCP4.5 at different time-scales. The rows show the four time-scales analysed in the study (1 months, 3 months, 6 months and 12 months) and the columns, the three temporal periods (2011-2040, 2041–2070 and 2071–2100). The maps are generated by interpolating the available stations over the territory.

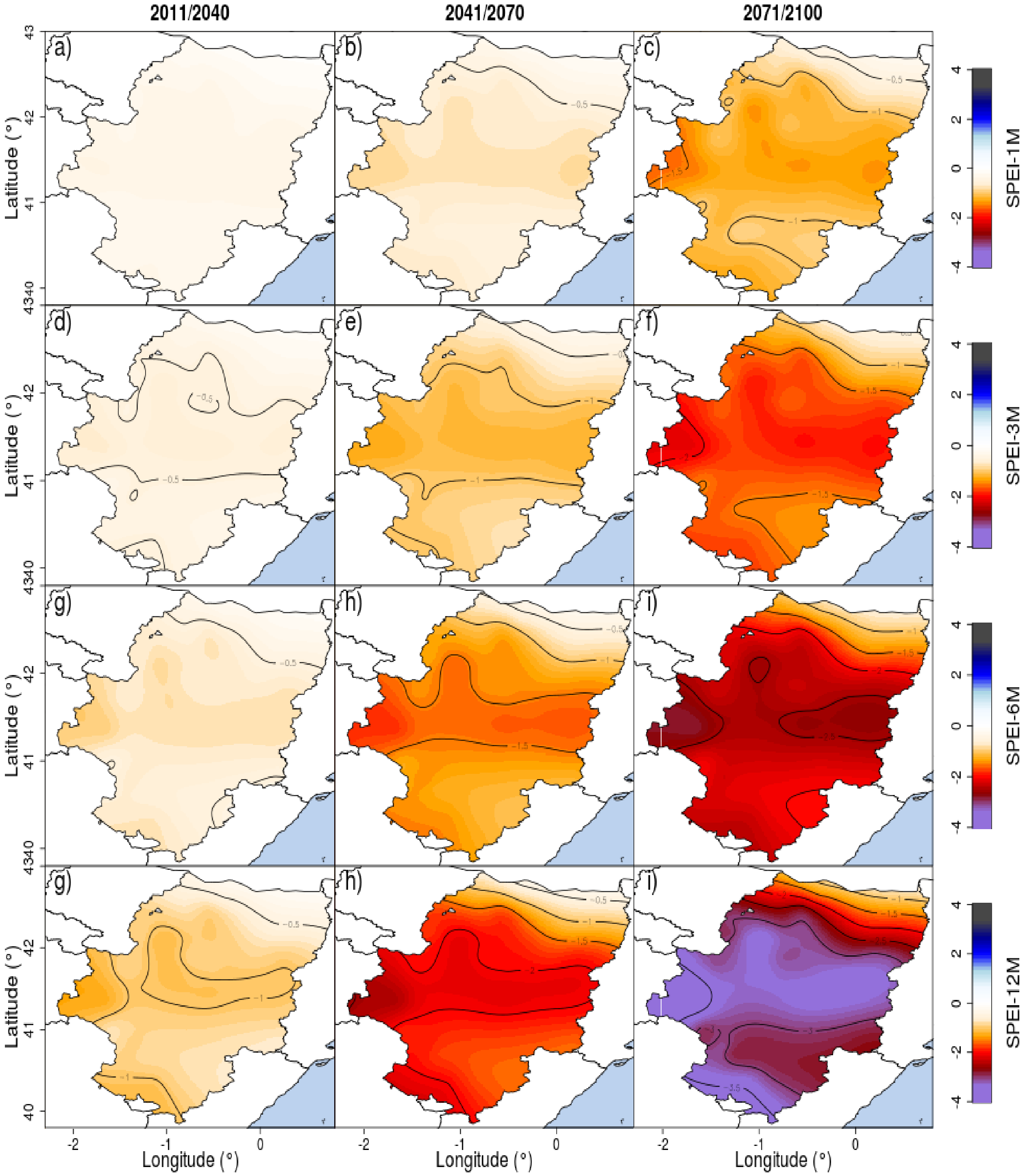

Figure 9. Time-scales SPEI maps under RCP8.5. Geographical representation of the expected evolution of the SPEI for Aragon in the periods 2041–2070 and 2071–2100 compared to the reference Historical Period (1971–2000) in terms of absolute values according to the RCP8.5 at different time-scales. The rows show the four time-scales analysed in the study (1 months, 3months, 6 months and 12 months) and the columns the three temporal periods (2011-2040, 2041–2070 and 2071–2100). The maps are generated by interpolating the available stations over the territory.

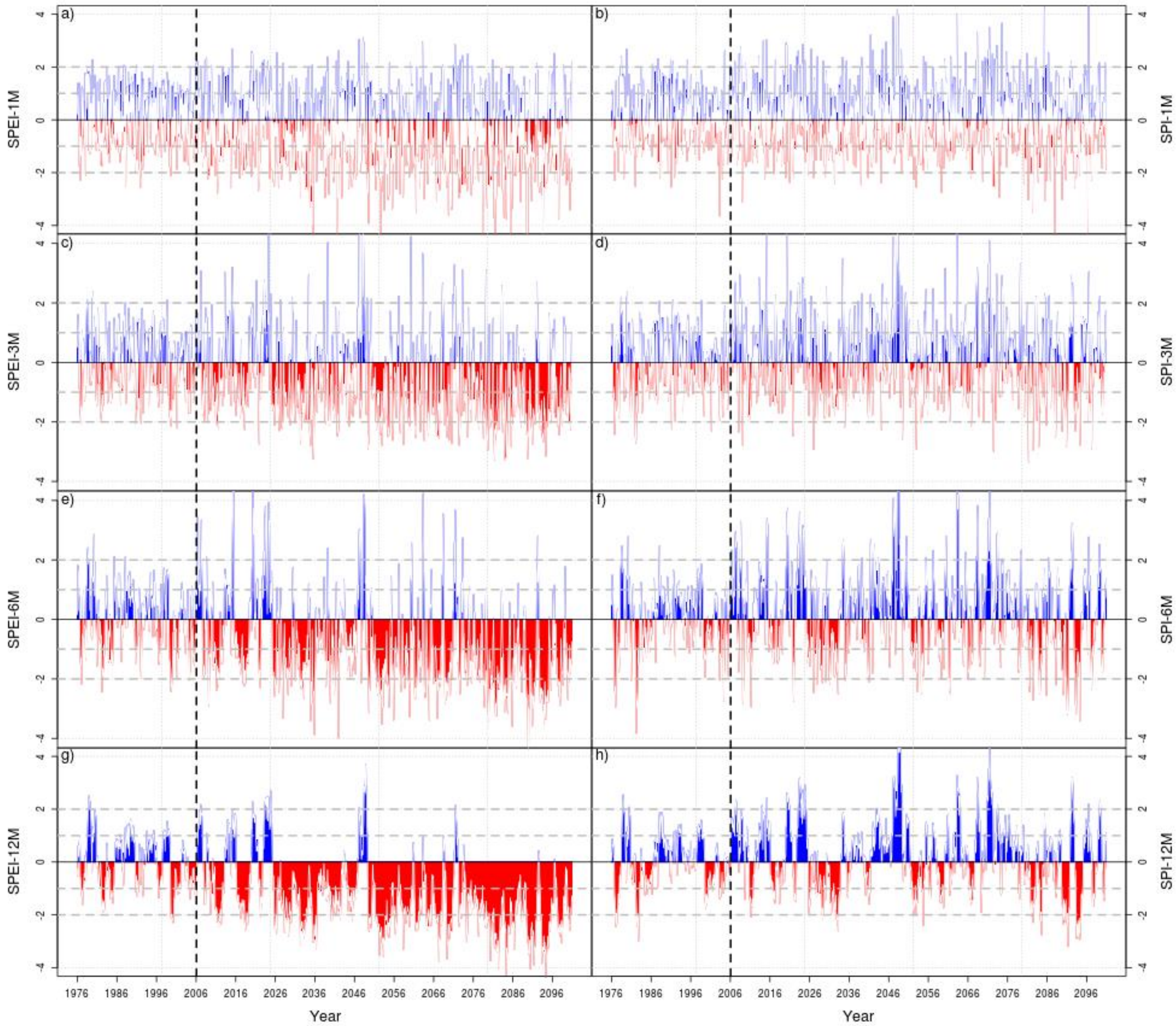

Figure 10. Time series for Zaragoza under MPI-ESM-MR RCP4.5. Evolution of the SPEI (first column) and the SPI (second column) based on the MPI-MR-SM model and under the RCP 4.5 at different time-scales - 1 month (first row), 3 months (second row), 6 months (third row) and 12 months (fourth row)- for Zaragoza.

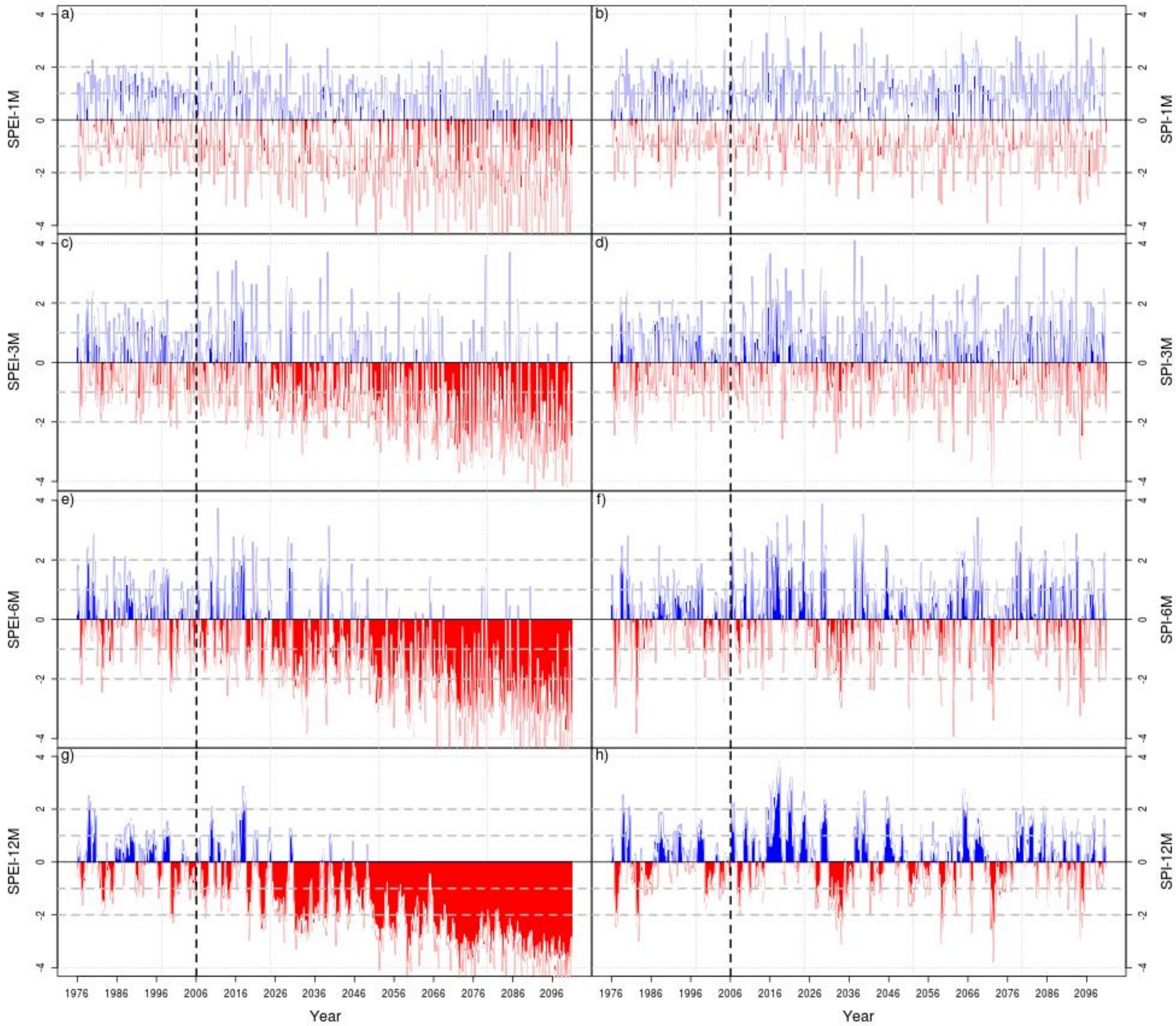

Figure. 11. Time series for Zaragoza under MPI-ESM-MR RCP8.5. Evolution of the SPEI (first column) and the SPI (second column) based on the MPI-MR-SM model and under the RCP 8.5 at different time-scales - 1 month (first row), 3 months (second row), 6 months (third row) and 12 months (fourth row)- for Zaragoza.

***Credit Author Statement**

individual contributions, using the relevant CRediT roles:

Author	Individual contributions
Emma Gaitan	Data curation, Formal analysis, Investigation; Methodology, Software, Validation, Writing original draft, review and editing
Robert Monjo	Data curation, Methodology, Software, final review.
Javier Pórtoles	Data curation, Methodology, Software, final review
Mª Rosa Pino-Otín	Formal analysis, Investigation; Methodology, Project administration, Supervision, Validation, Writing original draft, review and editing