



# Future changes of hot extremes in Spain: towards warmer conditions

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Received: 16 August 2021 / Accepted: 25 February 2022 / Published online: 21 March 2022  
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## Abstract

One of the most relevant effects of climate change is its influence on the frequency and intensity of extreme events. The analysis and understanding of these events are of great importance due to the probability of causing environmental and social damage. In this study, we investigate changes in extreme hot temperature events over Spain for the near future (2021–2050) in relation to a control period (1971–2000) by using regional climate model simulations from the EURO-CORDEX project. The projection results show a significant increase in the number of extremely warm temperatures throughout the area. A significant strong increase in warm days and warm nights is projected over the domain. Simulations also project more frequent summer days and tropical nights over most parts of the region. The most significant increase in relation to the present climatology corresponds to warm nights, while simulations corresponding to tropical nights project the smallest changes.

**Keywords** Extreme temperature indices · Warming scenarios · CORDEX · Iberian Peninsula

## 1 Introduction

Concern about climate change and its possible impacts on the biosphere has been on the rise over the last decades. General climate simulations for the end of the twenty-first century indicate a global temperature increase suggesting that this warming will not be regionally uniform. In this current context of climate change, there are new challenges that require us to make an effort to adapt to them in all aspects that surround humans. Human health constitutes one of these important challenges since it can be affected by changes in temperature extremes, especially in hot extremes (Patz et al. 2005; O’Neill and Ebi 2009). Future projections suggest that heat waves will occur more frequently and will last longer,

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while cold episodes are projected to decrease (Tebaldi et al. 2006; Beniston et al. 2007; Ballester et al. 2009; Orłowsky and Seneviratne 2011; Russo et al. 2014; Lorenzo et al. 2021). Heat waves are the main cause of mortality directly related to climate and its variations, clearly showing the risk of an increase in the intensity and frequency of these events. Urban populations, the elderly, or children can be vulnerable groups to extreme hot temperature events. The analysis of future changes in temperatures could, for example, help to prevent demands for hospital care from patients due to hot extremes. Thus, it would be possible to act in a more planned and global way on the population improving the effectiveness of urban heat island reduction or adapting the health system to the care needs as a result of these extreme events.

Temperature extremes can also affect short-term energy supply and demand (Schaeffer et al. 2012; Sathaye et al. 2013). The most immediate effect is that higher temperatures imply a reduction in demand for heating and higher demand for cooling. Nevertheless, temperature extremes can also affect other aspects of the energy sector, such as transmission and transfer of energy. A temperature rise could cause electric power transformer failures or decrease the capacity of a fully loaded transmission line.

Climate change can also cause damage to agriculture, forestry, and land uses increasing crop water consumption and reducing their production (Ciais et al. 2005; Lucena et al. 2009). Temperature increases could modify soil conditions producing shifts in the geographic distribution of crops or a decrease in available areas. The metabolism of insects can also be affected by increases in temperature, which could intensify the incidence of pests. Thus, the understanding of variations that occur concerning extreme hot temperature events supposes a great improvement of the human capacity to adapt to the problem and mitigate its effects.

Global climate models (GCMs) constitute an important tool to the international scientific community providing substantial information about future changes in the climate. Global climate projections in terms of extreme temperatures over the twenty-first century have been extensively analysed in numerous studies over the last decade (Tebaldi et al. 2006; Kharin et al. 2007, 2013; Sillmann and Roeckner 2008; Alexander and Arblaster 2009, 2017; Orłowsky and Seneviratne 2011; Russo and Sterl 2011; Sillmann et al. 2013). General results indicate an intensification of patterns of change in temperature indices worldwide. Extreme warm temperature is projected to increase, while extreme cold temperatures will become more moderate. Most of these studies reveal increases in warm day occurrences and heat wave lengths and decreases of cold extremes. The projected temperature change is also subject to variability in space indicating that the temperature increase at high latitudes will be much larger than near the equator.

Extreme temperatures have also been computed and analysed for projected future climate using regional climate models (RCMs) allowing for climate change assessment on a regional scale. Local studies are extremely necessary since the adaptation capacity of the different regions will depend on how climate change affects them. Several regional climatic simulations have been performed over Europe and the Mediterranean basin over the last years, where the Iberian Peninsula (IP) represents a sub-region of the study domain. These studies have revealed air temperature increases for all Europe and all seasons (Nikulin et al. 2011; Heinrich and Gobiet 2012; Keuler et al. 2016; Larsen et al. 2020). The most responsive regions are the northeastern parts of Europe in winter and southern Europe in summer. The largest future warming was detected in southern Europe showing a reduction of recurrence time of warm extremes and a probable disappearance of cold extremes (Nikulin et al. 2011; Heinrich and Gobiet 2012). This strong annual warming can be related to anomalous summertime warming (Keuler et al. 2016). Warming also increases for higher

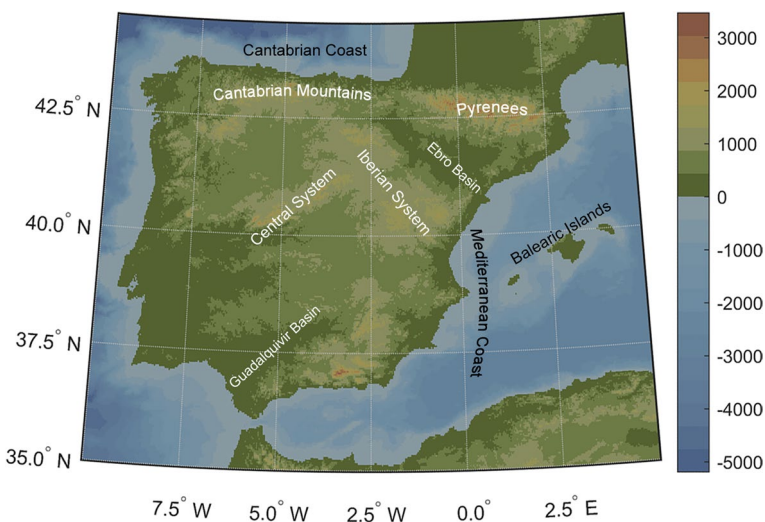
altitude areas such as the Alps, the Pyrenees and the Iberian Peninsula (Larsen et al. 2020). The number of hot days will increase which could lead to social, economic and ecological impacts due to heat waves (Beniston et al. 2007; Fischer and Schär 2009; Giorgi et al. 2014). The models also project more frequent temperature extremes particularly over the Mediterranean area (Fischer and Schär 2009; Ozturk et al. 2018).

The Iberian Peninsula (IP), located in the southwestern part of Europe, has been considered in the previous studies. Nevertheless, more local studies over this region are still necessary to obtain a comprehensive knowledge of future changes of extreme temperature indices. Spatial variations of temperatures over the IP are strongly influenced by its complex orography and distance from the sea promoting a marked climate gradient from the north to the south, as well as diurnal and seasonal thermal gradients from coastal to central areas (Fig. 1). Future changes in temperature extremes could lead to serious consequences on agriculture, ecosystems and human health highlighting the importance of climate information availability at regional resolutions. Thus, the objective of this work is to analyze future projections of temperature extremes over Spain under the assumption of various representative concentration pathways (RCP) (Moss et al. 2010; van Vuuren et al. 2011) using data from the EUROCORDEX project. These future projections provide high spatial resolution data focusing on grid-sizes of about 12 km ( $0.11^\circ$ ). Projections are considered for the period 2021–2050.

## 2 Data and methods

### 2.1 Observations

Daily temperature data over Spain were obtained from the Spain02 database developed by the Spanish Meteorological Agency (AEMET) and the University of Cantabria. These data are available between 1950 and 2008 in a wide network of meteorological stations (Herrera



**Fig. 1** Map of the studied area

et al. 2010, 2012, 2015). Data corresponding to the horizontal resolution of  $0.11^\circ$  were used in the present study. For more details on this database, the reader is referred to the page (<http://www.meteo.unican.es/en/datasets/spain02>).

## 2.2 Regional simulations

Simulations of daily maximum and minimum near-surface temperature data were obtained from the EURO-CORDEX project (<http://www.euro-cordex.net/>). This project provides regional climate projections over Europe considering the global climate simulations from the CMIP5 long-term experiments up to the year 2100 based on future climate scenarios considering larger amounts of data such as socioeconomic aspects or emerging technologies (Moss et al. 2010; Taylor et al. 2012; Jacob et al. 2014).

Temperature simulations were obtained from one RCM (RCA4) driven by five different global climate models (GCMs) over the period 1971–2050 (Table 1). The regional model RCA4 generally performs well when simulating the recent past climate taking boundary conditions from the GCMs. The EURO-CORDEX project also provides simulations from other RCMs although none of them has downscaled any large fraction of the CMIP5 GCMs at  $0.11^\circ$  resolution. In addition, this model has undergone substantial physical and technical changes compared to its predecessor RCA3 (Strandberg et al. 2014), is easily transferable and applicable for any domain worldwide and is efficient and user-friendly to operate (Kjellström et al. 2016). For more details on this climate model, the reader is referred to the page (<https://na-cordex.org/rcm-characteristics.html>).

The surface temperature was analysed considering two periods. The first one corresponds to the end of the twentieth century (1971–2000) and the second one to a near-future period (2021–2050). Future data were obtained from climate projections for two scenarios, RCP 4.5 and RCP 8.5 (Moss et al. 2010). Data were only considered until the year 2050 to analyse projections in the near future period. Knowing the short-term effects of climate change is important to take appropriate actions to help mitigate the long-term consequences of climate change.

Recent climate conditions (1971–2000) were firstly evaluated considering temperature from Spain02 dataset and simulations to assess the model's performance and to identify differences among the five simulations, taking into account Taylor diagrams. Diagrams show the correlation among time series, the centred root-mean-square (RMS) difference and the standard deviation ( $\sigma$ ) (Taylor 2001). The RMS and  $\sigma$  are normalized by the standard deviation of the reference Spain02 dataset to make the results of the indices comparable.

Projections (2021–2050) were evaluated considering a multimodel ensemble constructed by multiple linear regression (MLR) approaches (Lorenzo and Alvarez 2020).

**Table 1** Models considered to the analysis

Project	GCM	RCM
EURO-CORDEX	CNRM-CM5 EC-EARTH ICHEC IPSL-CM5A-MR HadGEM2-ES-MOHC MPI-ESM-LR	RCA4

MLR is a method of statistical analysis that estimates the relationship between a dependent (observed) variable and multiple independent variables (model outputs). This technique provides better results than using a multimodel ensemble mean (Krishnamurti et al. 1999, 2000, 2001).

## 2.3 Indices

Several climate indices from daily temperature were analysed. Table 2 shows a description of the indices used in the present work as defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). These indices were computed for Spain02 temperature data and EURO-CORDEX temperature simulations.

Among the chosen indices, those related to hot extremes during the day and also at night have been considered. The heat wave that affected Europe in 2003 showed that not only daytime temperature peaks and humidity variations should be monitored, but also night time ones, especially the presence of continued temperatures above normal at night. These temperatures, in addition to causing discomfort, can contribute to the increase in mortality by not allowing body temperature to return to baseline levels (Bouchama 2004; D’Ippoliti et al. 2010; Liss et al. 2017).

Future projections of temperature indices were analyzed by calculating differences between the future period (2021–2050) and the reference period (1971–2000). Significance was tested with a two-sided Wilcoxon rank-sum test, which is a nonparametric test for two independent samples. It can be used to evaluate whether the distributions of two independent samples are systematically different.

## 3 Results and discussion

Climate change is altering weather and climatology, and scientific evidence suggests that this could significantly affect the biosphere in the future. In many regions of the world, climate change is associated with an increase in extreme temperatures, which can have serious impacts on mortality, agriculture, energy supply, or indirect effects across different economic sectors. Therefore, it is necessary to carry out studies that analyze future projections of climatic variables such as temperature to improve the capacity to adapt to climate, as well as the quality of life of the population. Thus, in this work, the spatial pattern of different hot temperature indices was analysed over Spain for the next decades under two representative concentration pathways (RCP).

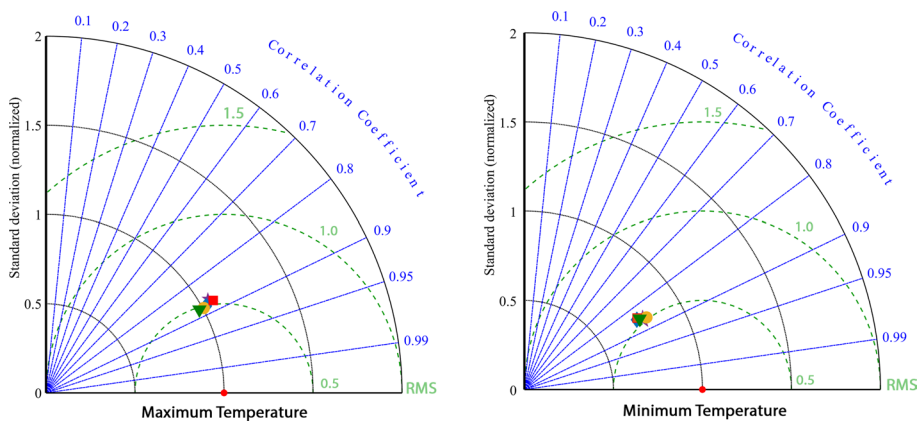
**Table 2** Extreme temperature indices. Note that SU35 is not an ETCCDI index

Index	Name	Description	Units
TX90	Warm days	Percentage of days when daily max temperature > 90th percentile	%
TN90	Warm nights	Percentage of days when daily min temperature > 90th percentile	%
SU	Summer days	Number of days when daily max temperature > 25°C	Days
SU35	Summer days	Number of days when daily max temperature > 35°C	Days
TR	Tropical nights	Number of days when daily min temperature > 20°C	Days

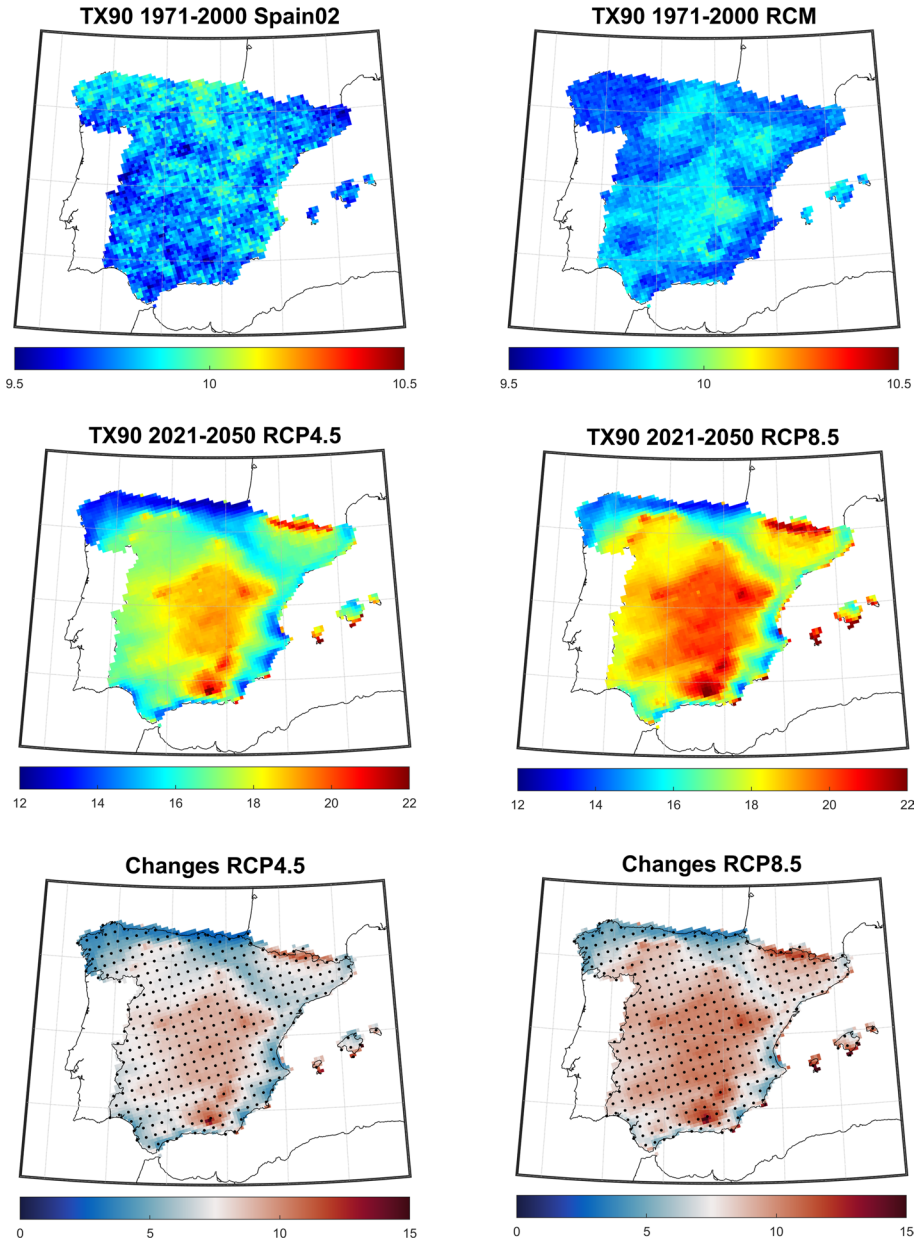
Before analyzing projected future temperature, the RCM performance in simulating observed climate was evaluated. Taylor diagrams were calculated considering maximum and minimum temperature averaged over the reference period to analyse the similarity between the modelled and observed data (Fig. 2). This type of diagram also provides information about inter-model differences in terms of the Pearson correlation coefficient ( $r$ ), the RMS difference and the standard deviation ( $\sigma$ ). The five points corresponding to the RCM simulations show the same behaviour among them, both for maximum and minimum temperature, indicating no significant inter-model differences among the simulations. The short distance to the reference point indicated by Spain02 (red dot) also shows a high model performance. The Pearson correlation coefficient reaches values close to 0.9, and the RMSD presents values around 0.5 indicating a good phasing between time series. Simulations corresponding to maximum temperature present values of the standard deviation over the line marking Spain02 data indicating a close agreement among the amplitude of the variations. On the other hand, the observed amplitude of variations for minimum temperature is slightly underestimated by the models with values of the standard deviation between 0.5 and 1.

Taking into account the good agreement between the five simulations, the spatial pattern of each index was evaluated by a model ensemble. Recent climate conditions were first evaluated for each index considering the observational dataset and simulations over the period 1971–2000. Then, possible changes in hot extremes were investigated for a near-future period (2021–2050) under two climatic scenarios, RCP 4.5 and RCP 8.5. The analysis of this period could help to better understand variations in extreme hot temperature events that will occur in the coming decades, helping to improve the human capacity to adapt to the problem and mitigate its effects.

Figure 3 shows the results for the TX90 index (warm days). The analysis of recent temperature conditions (1971–2000) indicates that simulations sufficiently reproduce the observed temperature climatology. A similar spatial distribution can be observed between both datasets with an annual mean percentage of warm days between 9–10% of days all over Spain. This pattern was also observed by Rodriguez-Puebla et al. (2010) for the period 1950–2006. They analysed the frequency of warm days using observations from



**Fig. 2** Taylor diagrams for maximum and minimum temperature for the comparison of Spain02 observations (red dot) and the five simulations (star-CNRM, diamond-ICHEC, circle-MPI, triangle-MOHC, square-IPSL) over the period 1971–2000



**Fig. 3** First row: annual mean of TX90 index (% of days) obtained from Spain02 observations and simulations for the period 1971–2000. Second row: annual mean of TX90 index (% of days) obtained from RCP 4.5 and RCP 8.5 scenarios for the period 2021–2050. Third row: Changes in projected TX90 index (% of days) for the period 2021–2050 concerning the period 1971–2000 for both scenarios. Grey dots mark the areas where changes are significant at the 5% significance level from the Wilcoxon rank-sum test. White colour in the colour scale represents the average increase in warm days (7.5% of days)

meteorological stations all over the Iberian Peninsula finding a mean value of the TX90 index around 10–12.

Figure 3 also shows the annual average pattern of the TX90 index along 2021–2050 for RCP 4.5 and RCP 8.5. Both scenarios project an important increase in the number of warm days throughout the territory concerning the present climatology (note the different values of the colour scale). The magnitude of warming projected by the RCP 8.5 scenario is more than that of the RCP 4.5 scenario. The highest number of warm days is obtained all over the central area of the IP and the Pyrenees with values around 20–22% of days. These data indicate an important change in the index increase in relation to the pattern observed for the period 1971–2000, where the average was 9–10% of days.

Changes in warm days for both scenarios with respect to the reference period (1971–2000) are also presented in Fig. 3. These changes were calculated as the difference between the near future period relative to the historical one, showing the change with respect to the average difference over the whole Peninsula. Both scenarios indicate a significant increase in the TX90 index in the whole area. These changes will become more intense for the RCP 8.5 scenario. The average increase (white colour) is about 7–8% of days for both scenarios with the highest changes observed in the central area of the country and the Pyrenees.

The TN90 index (warm nights) was also analysed. Figure 4 shows the TN90 pattern obtained from observations and RCM simulations over the period 1971–2000. The pattern described by Spain02 data reveals an annual mean percentage of warm nights around 10% of days all over Spain. Simulation results reflect a similar pattern where the maximum values are observed in the eastern part of the IP and along the northern coast.

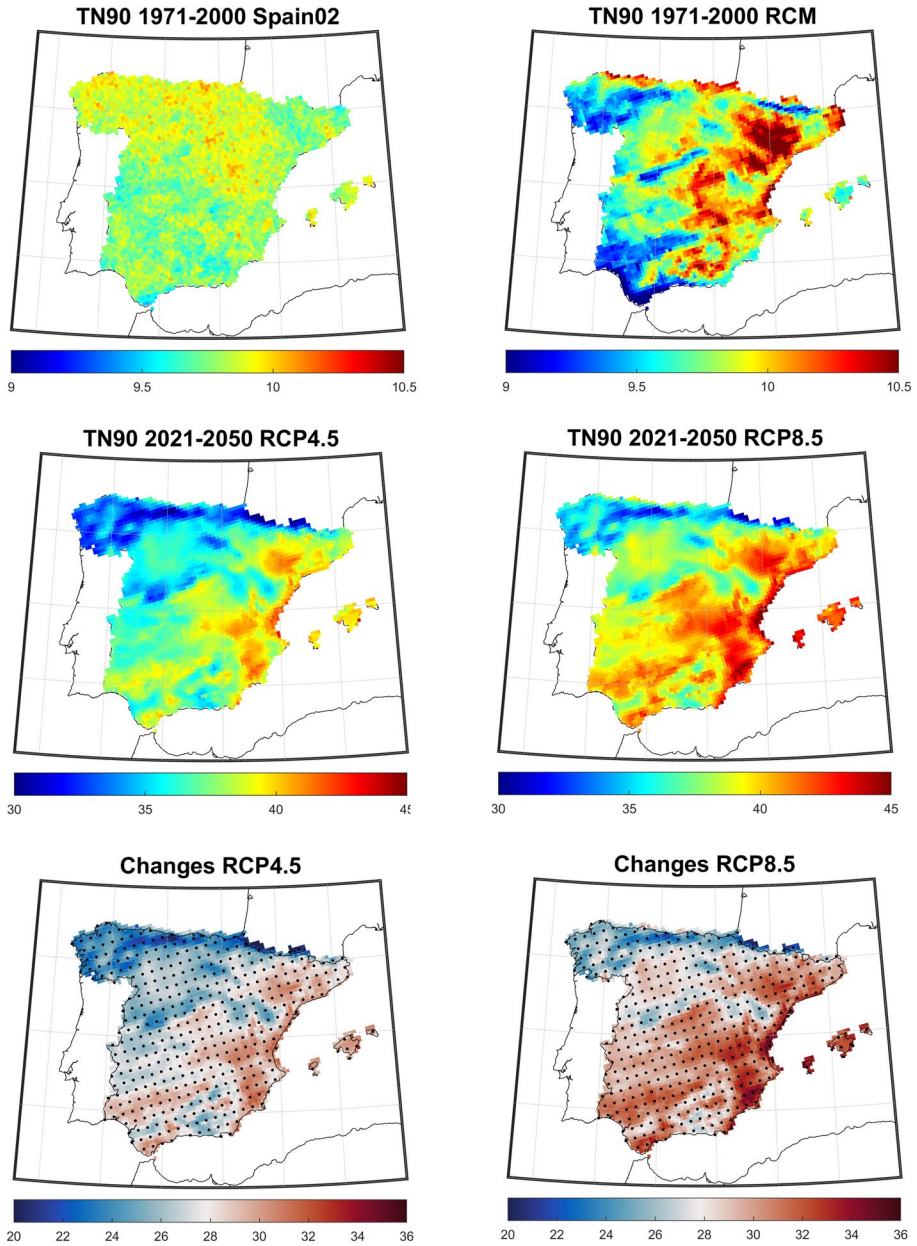
According to model results of future projections, the mean number of warm nights also presents higher values than those of the present period in the entire region under study for both scenarios (note the different values of the colour scale). The highest values of the TN90 index (45% of days) are obtained along the Mediterranean coast and the Ebro basin. As for warm days, the magnitude of warming projected by the RCP 8.5 scenario is more than that of the RCP 4.5 scenario.

From changes concerning the present climatology, it is possible to observe that simulations project an important increase in the TN90 index higher than in the TX90 index. These changes are significant in the whole area. The highest increase is concentrated over the southern area, the Mediterranean coast and the Balearic Islands. These data indicate a significant increase in warm nights concerning the pattern observed for the period 1971–2000, even doubling in some areas changes observed on warm days (Fig. 3).

As previously mentioned, rising temperature is one of the most important factors with direct effects on health. Several studies have found that extreme hot temperature events during the day can be associated with hospitalizations for cardiovascular and respiratory causes in Spain (Tobias et al. 2014; Linares et al. 2015; Carmona et al. 2016). Nevertheless, the presence of continued temperatures above normal at night is also an important factor that can contribute to the increase in mortality (Bouchama and Knochel 2002) highlighting the importance of the results obtained for warm nights.

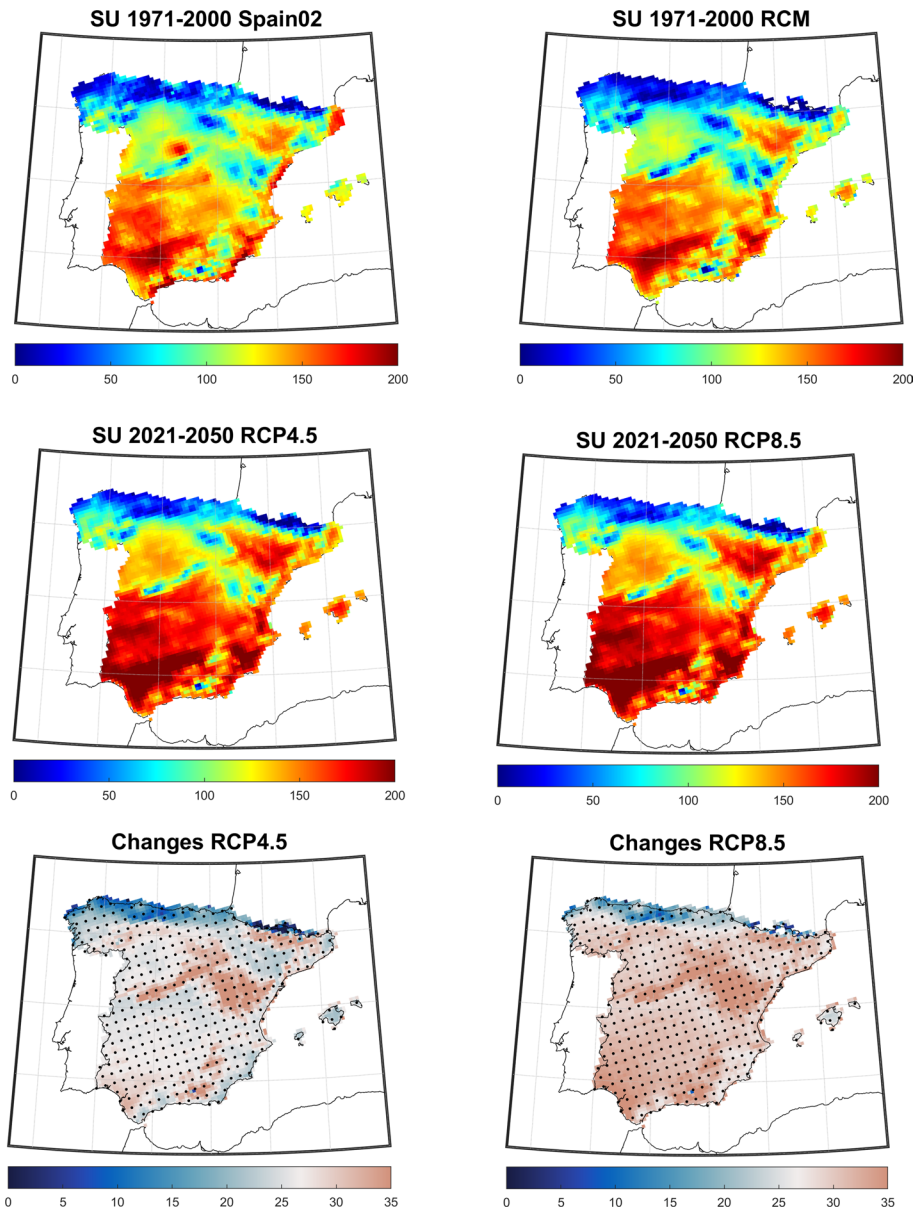
The projected increase in warm days and warm nights could also cause major impacts on society affecting energy demand, energy transmission, and distribution infrastructure. Thus, an increase in temperature can accelerate the aging of transformers or lead to efficiency losses (Schaeffer et al. 2012; Sathaye et al. 2013). The occurrence of extreme temperatures above a threshold could also have negative effects on agriculture and ecosystems with the intensification of droughts affecting crops fertility and productivity (Ciais et al. 2005; Lucena et al. 2009).





**Fig. 4** First row: annual mean of TN90 index (% of days) obtained from Spain02 observations and simulations for the period 1971–2000. Second row: annual mean of TN90 index (% of days) obtained from RCP 4.5 and RCP 8.5 scenarios for the period 2021–2050. Third row: Changes in projected TN90 index (% of days) for the period 2021–2050 concerning the period 1971–2000 for both scenarios. Grey dots mark the areas where changes are significant at the 5% significance level from the Wilcoxon rank-sum test. White colour in the colour scale represents the average increase in warm nights (28% of days)

Hot extremes over Spain were also analysed by the number of summer days (SU). This index can provide information on possible impacts on droughts, forest fires, and



**Fig. 5** First row: annual mean of SU index (days) obtained from Spain02 observations and simulations for the period 1971–2000. Second row: annual mean of SU index (days) obtained from RCP 4.5 and RCP 8.5 scenarios for the period 2021–2050. Third row: Changes in projected SU index (days) for the period 2021–2050 concerning the period 1971–2000 for both scenarios. Grey dots mark the areas where changes are significant at the 5% significance level from the Wilcoxon rank-sum test. White colour in the colour scale represents the average increase in summer days (27 days)

human health, among others (Garcia-Herrera et al. 2005; Trigo et al. 2006; Tobias et al. 2014). Comprehensive knowledge of future variations in this index could help to prevent adverse effects on multiple sectors such as agriculture or human health. Figure 5 shows the results for the SU index. Both datasets reveal the highest values of the SU index in the southern of the IP and along the Mediterranean coast including the Ebro basin and the Balearic Islands. The number of summer days decreases towards the north, especially over mountains and elevations such as the Cantabrian Mountains or the Pyrenees with values that scarcely exceed 20–30 days. Similar results were obtained by Fernandez-Montes and Rodrigo (2012) using data from observation stations from 1929 to 2005. Two areas were identified over the IP following the mean number of summer days with the maximum values obtained at the southern area.

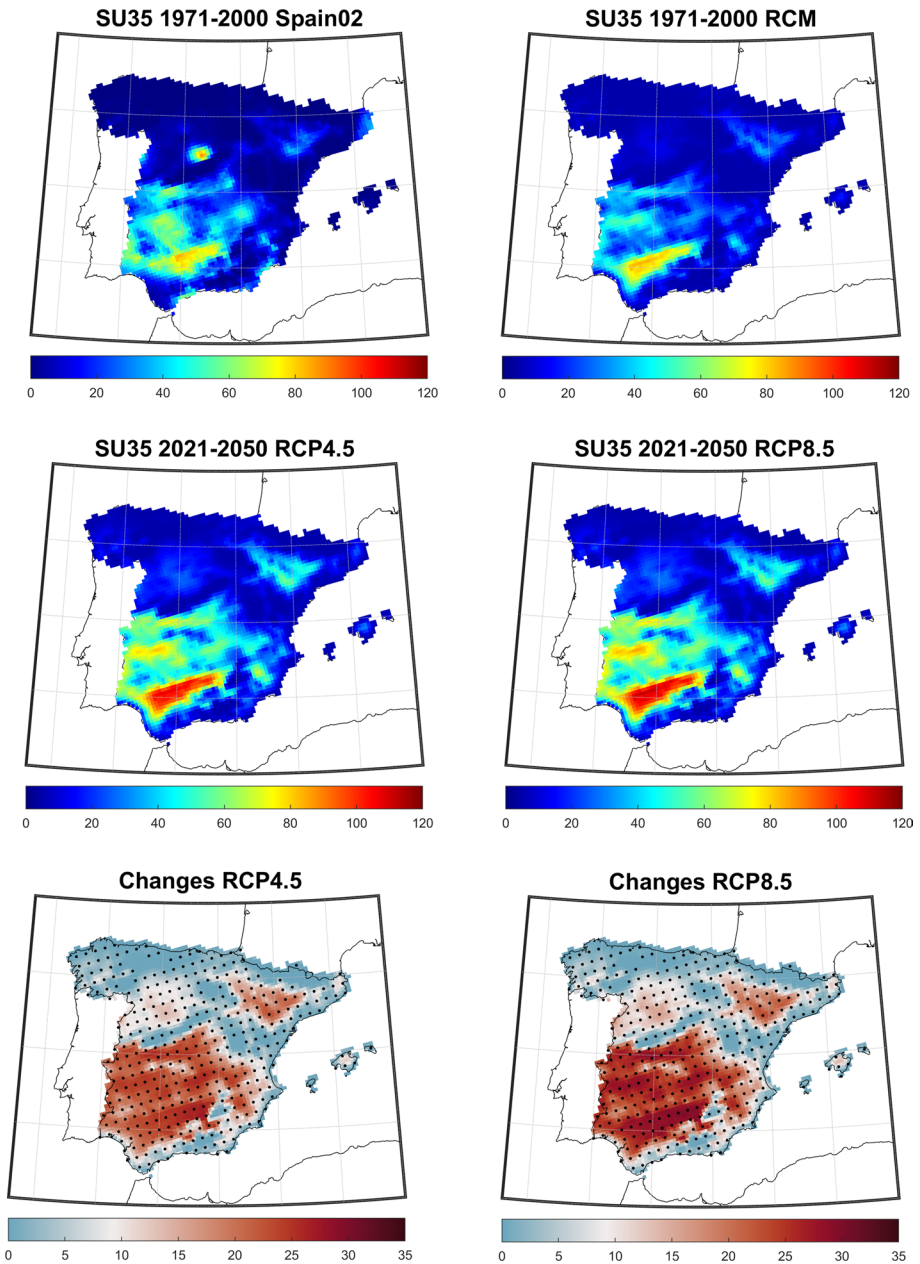
Simulations corresponding to a near-future period (2021–2050) project a general increase in the mean number of summer days for both scenarios. The highest values of the SU index can be observed all over the southern area with maximum values around 200 days over the Guadalquivir basin. The Balearic Islands and the Ebro basin also present an important increase in the SU index with values that can exceed 160 days.

The analysis of changes indicates that the increase in summer days with respect to the period 1971–2000 is significant all over the IP. Changes corresponding to the RCP 4.5 scenario show the highest difference over mountain areas as the Iberian System and the Central System reaching up to 35 days more than for the reference period. Positive changes around the average value of increase in summer days (25–30 days) are expected for the rest of the region except in the northernmost area where changes do not experience a significant increase. Results for the RCP 8.5 scenario show a similar spatial distribution although the amount of projected summer days is greater than for the RCP 4.5 scenario.

These results show a clear increase in summer days, especially in the southern area, which could lead to serious consequences for multiple sectors of society. Thus, high summer temperatures can be associated with adverse health effects and a high risk of mortality due to heat (Williams et al. 2012; Tobias et al. 2014; Chen et al. 2019; Singh et al. 2019). Urban populations can constitute a vulnerable group to these temperature extremes, making it necessary to improve the effectiveness of urban heat island reduction and extreme weather response plans (Estrada et al. 2017). On the other hand, the crop areas that extend through the south of Spain are characterized by large irrigated areas, so an increase in hot extremes could affect many key factors of agriculture, such as the crop yield and agricultural distribution areas. The intensification of irrigation due to temperature extremes could also enhance moist heat stress with a significant risk to human health (Mishra et al. 2020).

The analysis of the SU index was also complemented using a second threshold value (35 °C) defining the SU35 index (Fig. 6). This threshold 10 °C above the SU index can be used to define stronger extremes, which could increase human mortality, as well as energy utilization and negative impacts on agriculture (Choi et al. 2009; Fernandez-Montes and Rodrigo 2012). The number of days with temperature above 35 °C for the period 1971–2000 presents a similar spatial distribution for Spain02 data and RCM although simulations tend to slightly underestimate observations. The highest values are concentrated in the southern zone with SU35 values around 70–80 days. Data corresponding to Spain02 also show a small region with high values (80 days) in the central part which are not represented by the simulations.

Stronger extremes in summer days (SU35) were also investigated for the near future. The SU35 index presents the same spatial pattern as for the reference period with the highest values in the southern region. Simulations for both scenarios indicate an important



**Fig. 6** First row: annual mean of SU35 index (days) obtained from Spain02 observations and simulations for the period 1971–2000. Second row: annual mean of SU35 index (days) obtained from RCP 4.5 and RCP 8.5 scenarios for the period 2021–2050. Third row: Changes in projected SU35 index (days) for the period 2021–2050 concerning the period 1971–2000 for both scenarios. Grey dots mark the areas where changes are significant at the 5% significance level from the Wilcoxon rank-sum test. White colour in the colour scale represents the average increase in summer days (9 days)

increase in the number of summer days over the Guadalquivir basin with values around 110 days.

Changes in the SU35 index for the future concerning the present period based on both scenarios are also presented in Fig. 6. As in the previous index, changes are significant over almost the entire domain. Both scenarios present the same spatial distribution with some changes in magnitude. The most significant difference can be observed in the southern area with expected increases up to 25 days for the RCP 4.5 scenario and 30 days for the RCP 8.5 scenario. A significant increase (20 days) over the Ebro basin can be also observed for both scenarios. Over the rest of the region, it is also possible to observe an increase in the SU35 index below the average value (9 days).

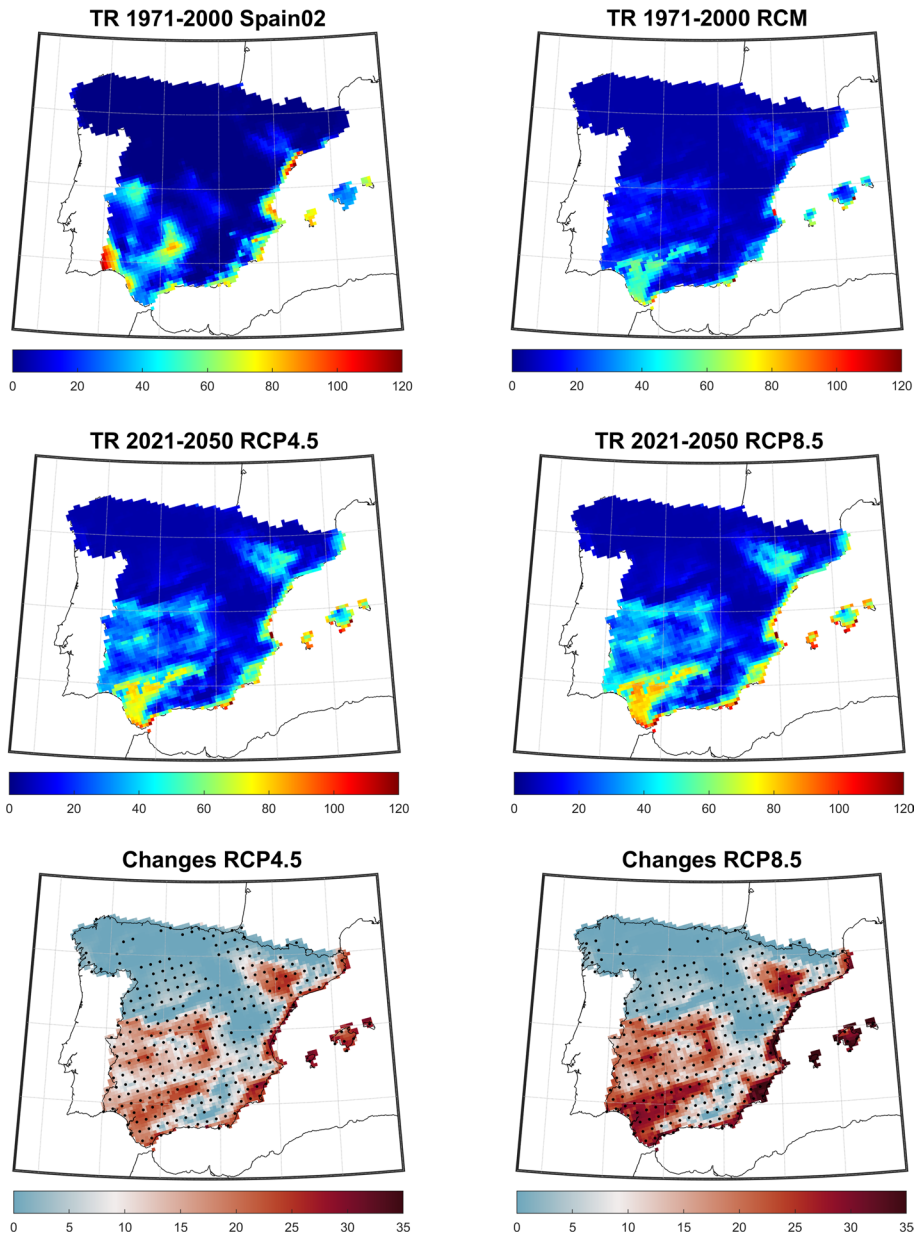
Changes in tropical nights (TR) were also analysed (Fig. 7). This index can provide information about possible heat stress for organisms (Sillmann and Roeckner 2008). On tropical nights (minimum temperature > 20 °C), the lowest temperature does not occur until shortly before dawn, and under temperatures above 25 °C sleep disturbances and rest can aggravate the consequences of extreme daytime temperatures (Bouchama and Knochel 2002; Royé et al., 2021). RCM output shows a good agreement in relation to the observational dataset. Nevertheless, simulations present lower maximum values than Spain02 data. The highest number of tropical nights is obtained at the southern area, over the Guadalquivir basin and along the Mediterranean coast with maximum values around 90 days for Spain02 and 60 days for simulations. Fernandez-Montes and Rodrigo (2012) also analysed tropical nights over the IP from 1929 to 2005 detecting a similar spatial pattern. They identified a clear division from northwest to southeast with a greater frequency of tropical nights along the Mediterranean coast.

According to the model results for the near future, there are no marked changes in the number of tropical nights all over the northern region. Results of both scenarios show an increase in the TR index concerning the present period for the southern area, the Mediterranean coast, the Ebro basin, and the Balearic Islands. The highest values (80–90 days) are detected over the Guadalquivir basin.

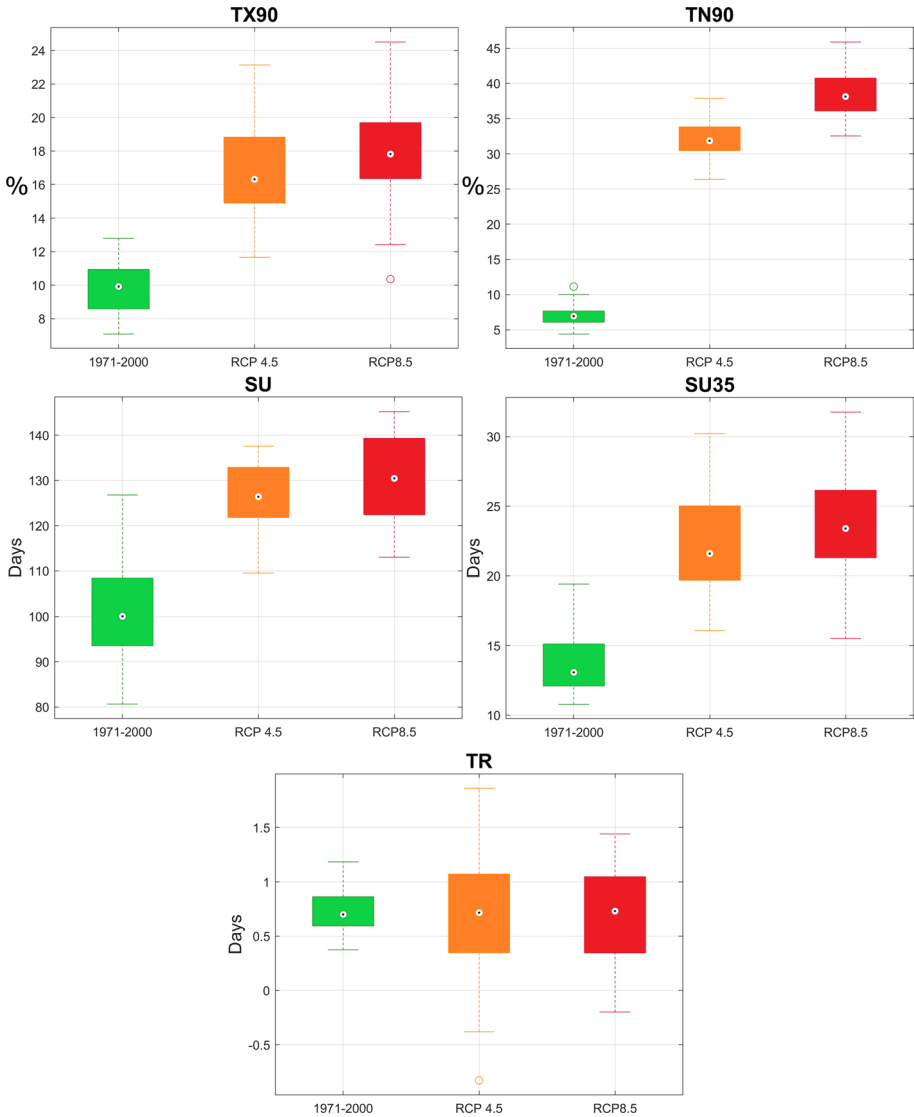
Changes in the TR index indicate that both scenarios show similar results for future projections. A significant increase up to 20–25 days in tropical nights is projected over the southern region of the IP and along the Mediterranean coast. Results based on the RCP8.5 scenario show much increase in this index, especially along the Mediterranean coast and the Balearic Islands, where increases of around 30–35 days are expected.

This increase in the frequency of tropical nights could have severe impacts on living conditions over the southern region of Spain and along the Mediterranean coast, being necessary measures of socio-economic adaptation of populations such as improved cooling systems and special health care for the elderly and children.

Figure 8 summarizes the results for the five indices. A spatial average has been considered for each index over the entire studied territory considering the RCM data, and results have been presented as a box-plot. All indices show an increase in the median of days with extreme temperatures concerning the present period (1971–200) for both scenarios. The difference between both future scenarios is not very large because for the period 2021–2050, both scenarios are not very different in their characteristics. However, it is possible to observe that all indices experience greater increases under the RCP 8.5 scenario. The most significant increase in relation to the present climatology corresponds to warm nights (TN90 index) as previously described in Fig. 4. On the other hand, simulations corresponding to tropical nights (TR index) project the smallest changes. Note that low values of the median for this index over the three periods analysed are due to the spatial average



**Fig. 7** First row: annual mean of TR index (days) obtained from Spain02 observations and simulations for the period 1971–2000. Second row: annual mean of TR index (days) obtained from RCP 4.5 and RCP 8.5 scenarios for the period 2021–2050. Third row: Changes in projected TR index (days) for the period 2021–2050 concerning the period 1971–2000 for both scenarios. Grey dots mark the areas where changes are significant at the 5% significance level from the Wilcoxon rank-sum test. White colour in the colour scale represents the average increase in tropical nights (9 days)



**Fig. 8** Summary of indices as box-whisker plots for the studied area. The black dot inside each box indicates the median, the boxes the interquartile range and the whisker the observed range

carried out. The spatial variations of this index all over Spain that have been previously analysed (Fig. 7) indicate that no marked changes were observed all over the northern region. Therefore, the spatial average dilutes the observed increases in specific areas such as the Guadalquivir and Ebro basin and hardly any changes are observed in the number of tropical nights.

## 4 Conclusions

This work investigates projected changes in hot extremes in Spain using simulations from the EURO-CORDEX project. Projections of different temperature indices from 2021 to 2050 were described under two concentration scenarios, RCP 4.5 and RCP 8.5. The ability of simulations to reproduce the observed temperature was investigated comparing model results and temperature data obtained from the Spain02 database for the present climatology (1971–2000). Results indicate that the RCM sufficiently reproduces the observed temperature climatology, although it slightly underestimates the temperature values.

According to model results of future projections, there will be a significant increase in the number of extreme hot temperature events all over the domain for both scenarios. The main results of this study are summarized as follows:

- Warm days (TX90) will experience an important increase throughout the territory with maximum values over the central area and the Pyrenees, where the increase could be double or even greater.
- The increase in the frequency of warm nights (TN90) will be even more noticeable than that of warm days in all parts of the domain. The largest increase will be concentrated over the southern area and the Mediterranean coast.
- The number of summer days (SU) will also increase throughout the domain with changes between 25 and 30 days showing the maximum change over the mountain systems.
- Strong hot extremes (SU35) events will increase as well over the Ebro basin and in the southern area of the IP with values near 20 days and 30 days, respectively.
- An increase in the number of tropical nights (TR) will occur for the southern area, the Mediterranean coast, the Ebro basin, and the Balearic Islands. The greatest increase is expected over the Mediterranean coast with values that could exceed 30 days.

The results obtained here show that for the near future important warmer conditions are expected to occur. The increase in warm days and warm nights will be very intense and stronger warm extremes will be more frequent, especially in the southern area. Thus, high temperatures will dominate significantly over the IP increasing the environmental risk of droughts and negative implications for human health.

**Acknowledgements** This work was partially supported by Xunta de Galicia, Consellería de Cultura, Educación y Universidad under project ED431C 2021/44 (Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas). I. Alvarez acknowledges financial support to CESAM by FCT/MCTES (UIDP/50017/2020+UIDB/50017/2020+ LA/P/0094/2020), through national funds.

**Funding** Open Access funding provided thanks to Universidade de Vigo/CISUG (CRUE-CSIC agreement with Springer Nature). The authors have not disclosed any funding.

## Declarations

**Conflict of interest** The authors declare that no conflict of interest.

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## References

- Alexander LV, Arblaster JM (2009) Assessing trends in observed and modeled climate extremes over Australia in relation to future projections. *Int J Climatol* 29:417–435. <https://doi.org/10.1002/joc.1730>
- Alexander LV, Arblaster JM (2017) Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5. *Weather Clim Extremes* 15:34–56. <https://doi.org/10.1016/j.wace.2017.02.001>
- Ballester J, Douville H, Chauvin F (2009) Present-day climatology and projected changes of warm and cold days in the CNRM-CM3 global climate model. *Clim Dyn* 32:35–54. <https://doi.org/10.1007/s00382-008-0371-0>
- Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, Goyette S, Halsnaes K, Holt T, Jylha K, Koffi B, Palutikof J, Scholl R, Semmler T, Woth K (2007) Future extreme events in European climate: an exploration of regional climate model projections. *Clim Change* 81:71–95. <https://doi.org/10.1007/s10584-006-9226-z>
- Bouchama A (2004) The 2003 European heat wave. *Intensive Care Med* 30:1–3. <https://doi.org/10.1007/s00134-003-2062-y>
- Bouchama A, Knochel JP (2002) Heat stroke. *N Engl J Med* 346:1978–1988. <https://doi.org/10.1056/NEJMra011089>
- Carmona R, Diaz J, Mirón II, Ortiz C, Luna MY, Linares C (2016) Mortality attributable to extreme temperatures in Spain: a comparative analysis by city. *Environ Int* 91:22–28. <https://doi.org/10.1016/j.envint.2016.02.018>
- Chen CC, Wang YR, Guo YL, Wang YC, Lu MM (2019) Short-term prediction of extremely hot days in summer due to climate change and ENSO and related attributable mortality. *Sci Total Environ* 661:10–17. <https://doi.org/10.1016/j.scitotenv.2019.01.168>
- Choi G, Collins D, Ren G, Trewin B, Baldi M, Fukuda Y, Afzaal M, Pianmana T, Gomboluudev P, Huong P, Lias N, Kwon W, Boo K, Cha Y, Zhou Y (2009) Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007. *Int J Climatol* 29:1906–1925. <https://doi.org/10.1002/joc.1979>
- Ciais P, Reichstein M, Viovy N, Granier A, Ogee J, Allard V, Aubinet M, Buchmann N, Bernhofer C, Carrara A, Chevallier F, De Noblet N, Friend AD, Friedlingstein P, Grünwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Loustau D, Manca G, Matteucci G, Miglietta F, Ourcival JM, Papale D, Pilegaard K, Rambal S, Seufert G, Soussana JF, Sanz MJ, Schulze ED, Vesala T, Valentini R (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437:529–533. <https://doi.org/10.1038/nature03972>
- D'Ippoliti D, Michelozzi P, Marino C, de' Donato F, Menne B, Katsouyanni K, Kirchmayer U, Analitis A, Medina-Ramon M, Paldy A, Atkinson R, Kovats S, Bisanti L, Schneider A, Lefranc A, Iñiguez C, Perucci A (2010) The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environ Health* 9(37):1–9. <https://doi.org/10.1186/1476-069X-9-37>
- Estrada F, Botzen WJW, Tol RSJ (2017) A global economic assessment of city policies to reduce climate change impacts. *Nat Clim Change* 7:403–406. <https://doi.org/10.1038/nclimate3301>
- Fernandez-Montes S, Rodrigo FS (2012) Trends in seasonal indices of daily temperature extremes in the Iberian Peninsula, 1929–2005. *Int J Climatol* 32:2320–2332. <https://doi.org/10.1002/joc.3399>
- Fischer EM, Schär C (2009) Future changes in daily summer temperature variability: driving processes and role for temperature extremes. *Clim Dyn* 33:917–935. <https://doi.org/10.1007/s00382-008-0473-8>
- Garcia-Herrera R, Diaz J, Trigo RM, Hernandez E (2005) Extreme summer temperatures in Iberia: health impacts and associated synoptic conditions. *Ann Geophys* 23:239–251
- Giorgi F, Coppola E, Raffaele F, Diro GT, Fuentes-Franco R, Giuliani G, Mamgain A, Llopart MP, Mariotti L, Torma C (2014) Changes in extremes and hydroclimatic regimes in the CREMA ensemble projections. *Clim Chang* 125:39–51. <https://doi.org/10.1007/s10584-014-1117-0>
- Heinrich G, Gobiet A (2012) The future of dry and wet spells in Europe: a comprehensive study based on the ENSEMBLES regional climate models. *Int J Climatol* 32:1951–1970. <https://doi.org/10.1002/joc.2421>

- Herrera S, Fita L, Fernández J, Gutiérrez JM (2010) Evaluation of the mean and extreme precipitation regimes from the ENSEMBLES regional climate multimodel simulations over Spain. *J Geophys Res* 115:D21117. <https://doi.org/10.1029/2010JD013936>
- Herrera S, Gutiérrez JM, Ancell R, Pons MR, Frías MD, Fernández J (2012) Development and analysis of a 50 year high-resolution daily gridded precipitation dataset over Spain (Spain02). *Int J Climatol*. <https://doi.org/10.1002/joc.2256>
- Herrera S, Fernandez J, Gutierrez JM (2015) Update of the Spain02 gridded observational dataset for Euro-CORDEX evaluation: assessing the effect of the interpolation methodology. *Int J Climatol* 36:900–908. <https://doi.org/10.1002/joc.4391>
- Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM, Braun A, Colette A, Deque M, Georgievski G, Georgopoulou E, Gobiet A, Menut L, Nikulin G, Haensler A, Hempelmann N, Jones C, Keuler K, Kovats S, Kroner N, Kotlarski S, Kriegsmann A, Martin E, van Meijgaard E, Moseley C, Pfeifer S, Preuschmann S, Radermacher C, Radtke K, Rechid D, Rounsevell M, Samuelsson P, Somot S, Soussana JF, Teichmann C, Valentini R, Vautard R, Weber B, Yiou P (2014) EURO-CORDEX: newhigh-resolution climate change projections for European impact research. *Reg Environ Chang* 14:563–578. <https://doi.org/10.1007/s10113-013-0499-2>
- Keuler K, Radtke K, Kotlarski S, Lüthi D (2016) Regional climate change over Europe in COSMO-CLM: influence of emission scenario and driving global model. *Meteorol Z* 25:121–136. <https://doi.org/10.3929/ethz-b-000117030>
- Kharin V, Zwiers FW, Zhang X, Hegerl GC (2007) Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. *J Climate* 20:1419–1444. <https://doi.org/10.1175/JCLI4066.1>
- Kharin VV, Zwiers FW, Zhang X, Wehner M (2013) Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Clim Change* 119:345–357. <https://doi.org/10.1007/s10584-013-0705-8>
- Kjellström E, Barring L, Nikulin G, Nilsson C, Persson G, Strandberg G (2016) Production and use of regional climate model projections – a Swedish perspective on building climate services. *Clim Serv* 2–3:15–29. <https://doi.org/10.1016/j.cliser.2016.06.004>
- Krishnamurti TN, Kishtawal CM, LaRow TE, Bachiochi DR, Zhang Z, Williford CE, Gadgil S, Suren-dran S (1999) Improved weather and seasonal climate forecasts from multimodel superensemble. *Science* 285:1548–1550. <https://doi.org/10.1126/science.285.5433.1548>
- Krishnamurti TN, Kishtawal CM, Zhang Z, LaRow T, Bachiochi D, Williford E (2000) Multimodel ensemble forecasts for weather and seasonal climate. *J Clim* 13:4196–4216. [https://doi.org/10.1175/1520-0442\(2000\)013%3c4196:MEFFWA%3e2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013%3c4196:MEFFWA%3e2.0.CO;2)
- Krishnamurti TN, Surendran S, Shin DW, Correa-Torres RJ, Vijaya Kumar TSV, Williford E, Kummerow C, Adler RF, Simpson J, Kakar R, Olson WS, Turk F (2001) Real-time multianalysis-multi-model superensemble forecasts of precipitation using TRMM and SSM/I products. *Am Meteorol Soc*. [https://doi.org/10.1175/1520-0493\(2001\)129%3c2861:RTMMSF%3e2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129%3c2861:RTMMSF%3e2.0.CO;2)
- Larsen MAD, Petrovic S, Radoszynski AM, McKenna R, Balyk O (2020) Climate change impacts on trends and extremes in future heating and cooling demands over Europe. *Energy Build* 226:110397. <https://doi.org/10.1016/j.enbuild.2020.110397>
- Linares C, Diaz J, Tobías R, Carmona R, Mirón IJ (2015) Impact of heat and cold waves on circulatory-cause and respiratory-cause mortality in Spain: 1975–2008. *Stoch Env Res Risk A* 29:2037–2046. <https://doi.org/10.1007/s00477-014-0976-2>
- Liss A, Wu R, Chui K, Naumova E (2017) Heat-related hospitalizations in older adults: an amplified effect of the first seasonal heatwave. *Sci Rep* 7:39581. <https://doi.org/10.1038/srep39581>
- Lorenzo MN, Alvarez I (2020) Climate changes in precipitation over Spain using CORDEX projections for 2021–2050. *Sci Total Environ* 723:1–24. <https://doi.org/10.1016/j.scitotenv.2020.138024>
- Lorenzo MN, Diaz-Poso A, Roye D (2021) Heatwave intensity on the Iberian Peninsula: future climate projections. *Atmos Res* 258:105655. <https://doi.org/10.1016/j.atmosres.2021.105655>
- Lucena AFP, Szklo AS, Schaeffera R, Souza RR, Borba BSMC, Costa IVL, Pereira AO, da Cunha SHF (2009) The vulnerability of renewable energy to climate change in Brazil. *Energy Policy* 37:879–889. <https://doi.org/10.1016/j.enpol.2008.10.029>
- Mishra V, Ambika AK, Asoka A, Aadhar S, Buzan J, Kumar R, Huber M (2020) Moist heat stress extremes in India enhanced by irrigation. *Nat Geosci* 13:722–728. <https://doi.org/10.1038/s41561-020-00650-8>
- Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463:747–756. <https://doi.org/10.1038/nature08823>

- Nikulin G, Kjellström E, Hansson U, Strandberg G, Ullerstig A (2011) Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations. *Tellus* 63A:41–55. <https://doi.org/10.1111/j.1600-0870.2010.00466.x>
- O'Neill MS, Ebi KL (2009) Temperature extremes and health: impacts of climate variability and change in the United States. *J Occup Environ Med* 51:13–25. <https://doi.org/10.1097/JOM.0b013e318173e122>
- Orlowsky B, Seneviratne SI (2011) Global changes in extremes events: regional and seasonal dimension. *Clim Change* 110:669–696. <https://doi.org/10.1007/s10584-011-0122-9>
- Ozturk T, Turp MT, Turkes M, Kurnaz ML (2018) Future projections of temperature and precipitation climatology for CORDEX-MENA domain using RegCM4.4. *Atmos Res* 206:87–107. <https://doi.org/10.1016/j.atmosres.2018.02.009>
- Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005) Impact of regional climate change on human health. *Nature* 438:310–317. <https://doi.org/10.1038/nature04188>
- Rodríguez-Puebla C, Encinas AH, García-Casado LA, Nieto S (2010) Trends in warm days and cold nights over the Iberian Peninsula: relationships to largescale variables. *Clim Change* 100:667–684. <https://doi.org/10.1007/s10584-009-9721-0>
- Royé D, Sera F, Tobias A, Lowe R, Gasparrini A, Pascal M, de' Donato F, NunesTeixeira BJP (2021) Effects of hot nights on mortality in Southern Europe. *Epidemiology* 32(4):487–498. <https://doi.org/10.1097/EDE.0000000000001359>
- Russo S, Sterl A (2011) Global changes in indices describing moderate temperature extremes from the daily output of a climate model. *J Geophys Res* 116:D03104. <https://doi.org/10.1029/2010JD014727>
- Russo S, Dosio A, Gravens RG, Sillmann J, Carrao H, Dunbar MB, Singleton A, Montagna P, Barbola P, Vogt JV (2014) Magnitude of extreme heat waves in present climate and their projection in a warming world. *J Geophys Res Atmos* 119:12500–12512. <https://doi.org/10.1002/2014JD022098>
- Sathaye JA, Dale LL, Larsen PH, Fitts GA, Koy K, Lewis SM, Lucena AFP (2013) Estimating impacts of warming temperatures on California's electricity system. *Global Environ Chang* 23:499–511. <https://doi.org/10.1016/j.gloenvcha.2012.12.005>
- Schaeffer R, Szklo AS, Pereira de Lucena AF, Borba BSMC, Nogueira LPP, Fleming FP, Troccoli A, Harrison M, Boulahya MS (2012) Energy sector vulnerability to climate change: a review. *Energy* 38:1–12. <https://doi.org/10.1016/j.energy.2011.11.056>
- Singh N, Mhawish A, Ghosh S, Banerjee T, Mall RK (2019) Attributing mortality from temperature extremes: a time series analysis in Varanasi, India. *Sci Total Environ* 665:453–464. <https://doi.org/10.1016/j.scitotenv.2019.02.074>
- Sillmann J, Roeckner E (2008) Indices for extreme events in projections of anthropogenic climate change. *Clim Change* 86:83–104. <https://doi.org/10.1007/s10584-007-9308-6>
- Sillmann J, Kharin VV, Zwiers FW, Zhang X, Bronaugh D (2013) Climate extremes indices in the CMIP5 multimodel ensemble: part 2. Future climate projections. *J Geophys Res Atmos* 118:2473–2493. <https://doi.org/10.1002/jgrd.50188>
- Strandberg G, Bärring L, Hansson U, Jansson C, Jones C, Kjellström E, Kolax M, Kupiainen M, Nikulin G, Samuelsson P, Ullerstig A, Wang S (2014) CORDEX scenarios for Europe from the Rossby Centre regional climate model RCA4. *Reports Meteorology and Climatology* 116 SMHI, SE-60176 Norrköping, Sverige
- Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. *J Geophys Res* 106:7183–7192. <https://doi.org/10.1029/2000JD900719>
- Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of Cmp5 and the experiment design. *Bull Am Meteorol Soc* 93:485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>
- Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to extremes: an intercomparison of model-simulated historical and future changes in extreme events. *Clim Change* 79:185–211. <https://doi.org/10.1007/s10584-006-9051-4>
- Trigo RM, Pereira JMC, Pereira MG, Mota B, Calado TJ, Dacamara CC, Santo FE (2006) Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. *Int J Climatol* 26:1741–1757. <https://doi.org/10.1002/joc.1333>
- Tobias A, Armstrong B, Gasparrini A, Diaz J (2014) Effects of high summer temperatures on mortality in 50 Spanish cities. *Environ Health* 13:1–6. <https://doi.org/10.1186/1476-069X-13-48>
- van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF, Masui T, Meinshausen M, Nakicenovic N, Smith SJ, Rose SK (2011) The representative concentration pathways: an overview. *Clim Change* 109:5–31. <https://doi.org/10.1007/s10584-011-0148-z>

Williams S, Nitschke M, Weinstein P, Pisaniello DL, Parton KA, Bi P (2012) The impact of summer temperatures and heatwaves on mortality and morbidity in Perth, Australia 1994–2008. *Environ Int* 40:33–38. <https://doi.org/10.1016/j.envint.2011.11.011>

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