

Analysis of extreme temperatures for four sites across Peninsular Spain

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Abstract Statistical analyses regarding climate studies have often used the average temperature as one of the main variables. However, the tails of the respective distributions are also crucial and have become increasingly considered in recent years. As the Intergovernmental Panel on Climate Change in its fourth assessment report (IPCC 2007) states, “the type, frequency and intensity of extreme events are expected to change as Earth’s climate changes”. In this paper, the focus is on the statistical behaviour of extreme (maximum and minimum) values of temperature, both in winter and summer. Under the framework of the Extreme Value Theory, the methodology of block maxima is employed. The generalised extreme value distribution, allowing for a linear trend in the location parameter, is fitted to data in order to capture the time tendency in the non-stationary processes. We are able to approximate expected values with a determined probability and to identify time trends of such events. Particularly, an increasing time trend in maximum and minimum temperature is generally detected which could be of great concern to public and private sectors.

Keywords Extreme values · Temperature · Block maxima

JEL classification Q54 · C16

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1 Introduction

Air temperature has an influence on virtually all human activities (health, agriculture, power supply, milk processing, infrastructure, forestry and ecosystems, among others). In particular, its impact on economic activity is well documented in literature. For instance, the interactions between climate and food production have been widely studied (McQuigg 1981; Huff and Neill 1982; Mearns et al. 1984). Colombo et al. (1999) concentrated on the implications of climate variability for power usage in Canada and a dependent relationship between temperature and demand for electricity over Peninsular Spain was pointed out in Cancelo and Espasa (1996), Valor et al. (2001) and Pardo et al. (2002).

These statistical analyses in climate studies use the average temperature as a variable. However, the greenhouse effect may not only lead to a change in average climate conditions, but also to an increase in climate variability. In this sense, the Intergovernmental Panel on Climate Change, in its fourth assessment report (IPCC 2007), states not only that “the recent increases in temperature have had perceptible impacts on many physical and biological systems” but also that “the type, frequency and intensity of extreme events are expected to change as Earth’s climate changes.” Naturally, the socioeconomic costs of those events are likely to increase in so far as extreme weather events occur more frequently and become more intense (Beniston 2004).

In this paper, we focus on the statistical behaviour of extreme values of temperature under the changing climatic conditions expected during the twenty-first century. Some examples of previous works also based on the statistics of extreme temperatures—because of their understandable effects on nature and humanity—are Domonkos et al. (2003), who centre their study on central and southern Europe, or Moberg et al. (2006) and Della-Marta et al.

(2007) dealing with data from the whole of Europe. Beniston et al. (2007) outline changes in various high-risk events that are most likely to affect Europe in forthcoming decades by analysing the results from a group of regional climate model simulations included in the European Union project PRUDENCE.¹ Within the framework of the project PRUDENCE, Dankers and Hiederer (2008), based on high-resolution simulations of the regional climate model HIRHAM (Christensen et al. 1996) project changes in temperature extremes in Europe by the end of the twenty-first century. Their results also suggest a general trend towards higher temperatures in the scenario period of 2071 to 2100 compared to the conditions of the control period 1961 to 1990.

One extreme event that has attracted much attention in the literature is the 2003 European heat wave (Beniston 2004; Fischer et al. 2004; Schär et al. 2004; Stedman 2004; Stott et al. 2004; Trigo et al. 2005; Siliverstovs et al. 2008; Kysely 2010). The 2003 summer was one of the hottest summers on record in Europe and led to health crises in several countries, particularly in France (WHO 2003). The probability of recurrence of annual temperature maxima and heat waves in the Czech Republic has been analysed by Kysely (2002), in which the AR(1) model and the generalised extreme value (GEV) distribution are compared, concluding that extreme value distributions should not be applied to maximum annual lengths of heat waves but may be used to estimate the recurrence probability of 1-day temperature extremes.

The interest in the study of extreme temperatures has increased in the last few years in Spain. In fact, this is one of the European countries where climatic change is expected to produce larger effects than in the rest of Europe² and extreme events have become one aspect of special interest in climate change studies. Brunet et al. (2007) analyse the evolution of annual changes of extreme temperature indices over mainland Spain for the period 1901–2005, finding increases (reductions) of the upper (lower) percentiles of the daily maximum and minimum temperature indices as well as a more marked warming of the minima from 1973. Prieto et al. (2004) focus on winter

minimum temperatures over Peninsular Spain for the period 1955–1998 and conclude that there is a generalised decreasing trend in the annual frequency of very cold days due to a global warming in the area.

Other works are centred on the study of extreme temperatures at a regional level, including, among others, Miró et al. (2006) who analyse summer (July and August) daily maximum and minimum temperatures (daily mean register of several stations grouped by location) in the Valencia region of Spain from 1958 to 2003; García et al. (2002) who are concerned about the incidence of extremely hot temperatures in the increase in mortality in Madrid; Lana and Burgueño (1996) who use the Gumbel I distribution and the general Jenkinson formulation (Jenkinson 1969) to model extreme minimum temperatures in Catalonia during the coldest months of the year (December, January, February and March), concluding that the former leads to more reliable models.

However, the literature mentions little about anomalously warm (cold) episodes outside the summer (winter) season. Focusing on the temperature maxima and minima for both the summer and winter seasons may be key for many industrial activities. Thus, extreme temperatures such as summer maxima and winter minima are expected to have as a consequence high levels of demand for electricity that may sometimes be difficult to address since electricity is non-storable.

Consequently, there is an obvious interest within the public and private sectors in the future pattern of extreme temperatures under the expected changing conditions during the present century. Hence, being able to approximate the frequencies and to identify time trends of such events could be profitable for firm managers as well as being helpful for defining the strategies for adapting to climate change.

The modelling of extreme events is the central issue in extreme value theory, and the main purpose of this theory is to provide asymptotic models for the distribution tails. Thus, we turn to the field of extreme value theory as a theoretical framework to describe the dynamics of extreme temperature values and apply the so-called block maxima approach. We deal with daily temperature maxima and minima for winter and summer, separately, for each year, and from four weather stations located in four different climate areas of Spain. Furthermore, we analyse four yearly series: winter temperature maxima, winter temperature minima, summer temperature maxima and summer temperature minima.

The maximum likelihood method is used to fit the GEV model to maxima (and minima) data. In the present study, as extreme temperature data appears to exhibit an increasing trend over the studied periods, the non-stationary GEV distribution is applied in order to determine whether the apparent non-constant mean is a characteristic of the process that should not be ignored when fitting the model to data. By doing so, we are able to go beyond the

¹ Prediction of Regional scenarios and Uncertainties for Defining EuropeN Climate change risks and Effects (Christensen et al. 2007).

² Della-Marta et al. (2007) analyse daily maximum temperature series from Western Europe concluding that mean temperature change is expected to be the highest over Southern Europe and the Iberian Peninsula; Dankers and Hiederer (2008) find that on average the mean daily temperature is projected to increase over almost all parts of Europe and, especially, in Spain, the Alps, the southern Balkans and Finland showing increases of up to 6°C. Finally, Beniston et al. (2007) state that much higher increases are predicted for the mean intensity, the mean number of heat waves and the frequency of heat wave days, with the greatest changes (more than tenfold increases) in the south of France and Spain.

characterization of the behaviour of the extreme temperature series, and, by extrapolation, to provide expected values of the maximum and minimum temperature both in summer and winter with a fixed probability according to different time horizons.

The goal of the paper is then twofold: (1) to study the behaviour of the involved extreme temperature series over time, which will allow us to compare our results with those of previous works and (2) to obtain estimations of extreme temperature levels in the future, according to their behaviour observed over the studied samples.

This paper contributes to the literature by extending the analysis of approximating expected values with a determined probability and identifying time trends of such events to four climate-representative Spanish sites. Moreover, we deal not only with the summer and winter minima but also with the summer and winter maxima because changes in the latter also have an impact on industrial activity.

The remainder of this paper is organised as follows. In Section 2 the theoretical framework of the methodology used is presented. Section 3 describes and carries out a preliminary analysis of the data set. Section 4 is concerned with the estimation of the GEV model for extreme temperature events, with special emphasis in the trend detection. Finally, Section 5 summarises the results and concludes.

2 Extreme value theory

The extreme value theory relies on two main general definitions of extreme events. Following the first one, data are taken to be the maxima (or minima) over certain blocks of time. In this context, it is appropriate to use the GEV distribution. The second specification of extreme events consists of extracting those values that exceed a properly chosen threshold. These exceedances, when independent, follow a generalised Pareto distribution. See Leadbetter et al. (1983), Embrechts et al. (1999) and Coles (2003) for an introduction to and application of extreme value theory.

The block maxima approach compared to the peak over threshold approach presents a shortcoming: as just one extreme per year is chosen, completeness of the statistical population is not guaranteed. In fact, the former implies a loss of information that may be important, since the latter allows for more data to be incorporated in the analysis. Following the first approach, the series used in the present study are constructed by determining the maximum (and minimum) temperature for each of the studied seasons (summer and winter), so the series length equals the number of years for which data is available, which is different according to the recording site. Under the framework of the second approach, the extreme temperature series is made up of the values above (below) a selected

threshold regardless of the year in which they occurred. The main problem here involves the selection of the threshold, as the results may vary greatly depending on its value (Vicente-Serrano and Beguería-Portugués 2003).

2.1 Block maxima

In this paper, we focus on the block maxima approach, according to which the model focuses on the statistical behaviour of

$$M_n = \max\{X_1, X_2, \dots, X_n\},$$

where X_1, X_2, \dots, X_n is a sequence of independent random variables having a common distribution function F . In the context of this work, the X_i stands for values of the daily extreme temperature process and M_n represents the maximum of the process over n time units of observation. For instance, if n is the number of observations over the summer season in a year, then M_n is the annual summer maximum. The distribution function is:

$$\begin{aligned} \Pr\{M_n \leq z\} &= \Pr\{X_1 \leq z, \dots, X_n \leq z\} \\ &= \Pr\{X_1 \leq z\} \times \Pr\{X_2 \leq z\} \times \dots \times \Pr\{X_n \leq z\} \\ &= \{F(z)\}^n \end{aligned}$$

As argued in Leadbetter et al. (1983), the distribution of the maximum of identically distributed random variables is well approximated by the GEV distribution, with three parameters: a location parameter, μ ; a scale parameter, σ ; and a shape parameter, ξ .

$$F(z; \mu; \sigma; \xi) = \exp\left\{-\left[1 + \xi\left(\frac{z - \mu}{\sigma}\right)\right]^{\frac{-1}{\xi}}\right\}, \quad (1)$$

defined on $\left\{z: \frac{1 + \xi(z - \mu)}{\sigma} > 0\right\}$, where $-\infty < \mu < \infty$, $\sigma > 0$ and $-\infty < \xi < \infty$.

Parameter ξ is known as the tail index. If $\xi > 0$, it corresponds to the Fréchet distribution; if $\xi = 0$, to the Gumbel distribution and if $\xi < 0$, to the Weibull distribution. The unification of these three families of extreme value distributions into a single family greatly simplifies statistical implementation. Through inference on ξ , the data themselves determine the most appropriate type of tail behaviour, and there is no necessity to make subjective a priori judgements about which individual extreme value family to adopt (Coles 2003).

Asymptotic arguments support the use of the GEV distribution for modelling the extreme temperature of winter or summer in any year, but the presence of any time trend in the data raises doubts about the suitability of the conventional model which assumes a constant mean over time.

The non-stationarity might be accounted for by letting the location parameter in the GEV distribution depend on the time (e.g., Smith 1989). Using the notation $GEV(\mu, \sigma, \xi)$

Fig. 1 Map of Peninsular Spain showing the four weather stations



to denote the GEV distribution with parameters μ , σ and ξ , it follows that a suitable model for the extreme temperature in year t , Z_t , might be

$$Z_t \approx GEV(\mu(t), \sigma, \xi) \quad (5)$$

where $\mu(t) = \beta_0 + \beta_1 t$. The parameter β_1 corresponds to the annual rate of change in the extreme temperature series. In order to select the most suitable model, we use the likelihood ratio test (Coles 2003).

The estimation technique used for the GEV parameters (μ , σ , ξ) is the maximum likelihood method. It should be mentioned that there is a potential difficulty with the use of likelihood methods that relies on the regularity conditions required for the usual asymptotic properties associated with the maximum likelihood estimator to be valid. After studying this question in detail, Smith (1985) concluded that when $\xi > -0.5$, maximum likelihood estimators are regular, in the sense of having the usual asymptotic properties.³

The series of minima requires a model for extremely small, rather than extremely large, observations. The lower tail extremes can be handled by taking the negative transformation (the sequence $-X_n$ instead of the sequence X_n) and simply applying the same techniques as for maxima (Coles 2003). Thus, the GEV can be directly fitted to the sample maxima and used to obtain the probability of occurrence of large temperatures. Then, the maximum

likelihood estimate of the parameters of this distribution only requires the sign correction of the location parameter ($\hat{\mu} = -\tilde{\mu}$).

3 Data

The temperature data set consists of a series of daily maximum and minimum air temperatures (°C) recorded at four weather stations located in Bilbao (Bilbao Airport observatory), Madrid (El Retiro observatory), Seville (Tablada Airport observatory) and Valencia (Valencia Airport observatory) which are, respectively, distributed in the north, central, south and east of Peninsular Spain (Fig. 1).

In order to deal with meteorological data collection as accurately as possible, these weather stations across Peninsular Spain were chosen for study according to two criteria:

- (1) Sites having a relatively long historical record and being as complete as possible. In fact, the length of the historical record is crucial in reducing sampling error in the evaluation of empirical event probabilities and for better assessment of the probability distribution (Nicholls 1995).

The data availability differs from location to location. Thus, the data for Bilbao, Madrid, Seville and Valencia cover the periods: March 1947–July 2009, January 1900–July 2009, January 1922–July 2009 and January 1938–July 2009, respectively. The winter (summer) daily temperature time series is constructed by joining from 21st December to 20th March (21st June to 20th

³ Otherwise, when $-1 < \xi < -0.5$, maximum likelihood estimators are generally obtainable, but do not have the standard asymptotic properties, and finally when $\xi < -1$, maximum likelihood estimators are unlikely to be obtainable.

September) of each year in chronological order, so that the sample size of each series is 90 (92) days multiplied by the number of years in each case.

Regarding the completeness, the series of temperature data for Valencia is complete, while Bilbao, Madrid and Seville temperature datasets present 1.6%, 0.3% and 2% of missing data. Although data gaps are filled in some works, as we are interested in the maximum (and minimum) temperature over each season, no attempt to fill in gaps (for instance, by averaging the previous and the next value or repeating the last available value) has been performed in the present study.

- (2) Sites being representative of the major Spanish climate types. According to the Spanish climate classification of Martín-Vide and Olcina (2001), the main Spanish climate types are Atlantic and Mediterranean, being the subtypes applicable for the selected sites: Atlantic, Mediterranean Continental, Southern Mediterranean and Mediterranean Eastern coast, respectively for Bilbao, Madrid, Seville and Valencia.

Data quality of the analysed series is expected to be fairly good because all of them have been provided by the Spanish Meteorological Office and hence they are assumed to be highly monitored and well quality-controlled. Nevertheless, several quality control procedures have been applied in order to identify potential errors introduced when recording, formatting, archiving or transmitting the data. These tests have been suggested by Aguilar et al. (2003) and employed, for instance, in Brunet et al. (2006), Martínez et al. (2010): (1) gross error checking (consistency of calendar dates, that is, number of days per month; records exceeding unlikely temperatures, i.e. maximum (minimum) temperatures $>$ ($<$) 50°C (-50°C), (2) tolerance test (periods longer than four consecutive days with the same temperature), (3) internal consistency check consisting of verifying that maximum temperature always exceeds minimum temperature for every calendar day, and (4) temporal coherency (values exceeding a 25°C difference between consecutive observations).

Errors detected by the first (gross error checking), third (internal consistency) and fourth (temporal coherency) procedures are null. The tolerance check only found a ratio of incidences of 0.03% and 0.07% for the temperature datasets corresponding to Seville and Valencia, respectively. To summarise, from 120,118 records checked, only 19 incidences have been identified, meaning 0.02% of data. These values have been inspected one-by-one in the original sources. Most of them have been validated and retained in the dataset as true values and, in the rest of the cases, they have been converted to missing values.

Of concern was the potential influence of heat islands from large urban centres on temperature records. The

airport weather stations are located far enough outside from the downtown core of the corresponding cities, where the urban heat island effect does not noticeably affect temperature readings. Only El Retiro observatory is within the Madrid metropolitan area, though situated in El Retiro park. Weather stations located in parks within urban areas are frequently referred to “cool islands”. Nevertheless, the urban heat island effect in Madrid has been studied by Almarza (2000), showing an artificial trend between 1894 and 1960 in Madrid’s records, when the city experienced a strong expansion. According to his findings, although the city went on growing after 1960, the urban influence on temperature records has vanished since then.

This result led us to investigate whether the results for Madrid remained the same during the sample period which is assumed to be free of the urban heat island effect, that is 1960–2009, if compared to those obtained for the whole sample period, i.e. 1900–2009.

4 GEV model for temperature data

To begin, independence of observations is required for the observations of extremes. The temperature extremes are defined as the highest and the lowest daily temperature for winter and summer, separately. Therefore, our block size is one season. The fact that each extreme observation belongs to a different year is sufficient to ensure independence.

As highlighted in the introduction, since human activity is expected to be influenced by expected and/or unexpected increases in temperature, as well as by expected and/or unexpected drops, we finally opt to deal with four series of annual extreme temperature: (1) summer maximum temperature (*sum_maxt*), (2) summer minimum temperature (*sum_mint*), (3) winter maximum temperature (*win_maxt*) and (4) winter minimum temperature (*win_mint*).

Table 1 shows some representative statistics of the series. Note that the series of minimum temperature in winter and maximum temperature in summer are the most volatile ones in Valencia, while it is during the winter (summer) season that minima and maxima fluctuate the most in Madrid and Seville (Bilbao). The difference between the extreme data in absolute terms within a season is noteworthy. In fact, the difference between the maximum temperature and the minimum temperature in winter (summer) varies between 34.8°C (34.5°C) and 38.0°C (38.2°C), depending on the different sites.⁴ In summer, the hottest site is Seville with an average maximum temperature of 42.1°C followed by Bilbao (37.1°C), Madrid (36.7°C) and Valencia (36.7°C). The average minimum temperature in winter is -3.3°C in

⁴ Caution is needed when making comparisons between the cities because they have different sample sizes.

Table 1 Descriptive statistics of extreme temperature series

	Sum_maxt	Sum_mint	Win_maxt	Win_mint
Panel A: Bilbao (1947–2009)				
Mean [°C]	37.1	8.1	23.9	−3.3
Median [°C]	36.7	8.0	23.8	−3.0
Maximum [°C]	42.0	12.4	27.8	0.4
Minimum [°C]	30.0	4.4	19.6	−8.6
Std. Dev. [°C]	2.3	1.6	2.3	1.8
Skewness	0.0	0.1	0.1	−0.8
Kurtosis	0.4	0.4	−1.1	0.9
Panel B: Madrid (1900–2009)				
Mean [°C]	36.7	9.9	20.0	−4.2
Median [°C]	36.7	10.0	20.0	−3.6
Maximum [°C]	40.0	13.6	25.8	0.4
Minimum [°C]	33.2	4.4	14.6	−10.1
Std. Dev. [°C]	1.4	1.9	2.2	2.3
Skewness	−0.2	−0.5	0.1	−0.4
Kurtosis	−0.2	0.1	−0.4	−0.3
Panel C: Sevilla (1922–2009)				
Mean [°C]	42.1	12.5	25.1	−0.8
Median [°C]	42.0	12.6	25.2	−1.0
Maximum [°C]	45.4	15.4	30.2	4.6
Minimum [°C]	37.4	7.2	20.4	−4.6
Std. Dev. [°C]	1.6	1.7	2.2	2.2
Skewness	−0.1	−0.5	−0.1	0.2
Kurtosis	−0.2	−0.3	−0.5	−0.5
Panel D: Valencia (1938–2009)				
Mean [°C]	36.7	14.8	25.6	0.4
Median [°C]	36.6	15.0	25.4	0.6
Maximum [°C]	42.5	18.4	30.8	4.4
Minimum [°C]	31.6	8.0	21.0	−7.2
Std. Dev. [°C]	2.3	1.9	2.0	2.2
Skewness	0.3	−0.8	0.4	−1.1
Kurtosis	0.1	1.5	0.1	2.0

Table 1 shows some representative statistics of the series of maximum and minimum temperatures both in winter and summer for each of the considered sites. Sum_maxt, Sum_mint, Win_maxt and Win_mint refer to summer maximum temperature, summer minimum temperature, winter maximum temperature and winter minimum temperature, respectively. The winter of 1900 covers from 21st December 1900 to 20th March 1901 and so on

Bilbao, -4.2°C in Madrid, -0.8°C in Seville and 0.4°C in Valencia. Just for comparative purposes, we have restricted each of the samples to a subset of 62 years (i.e. from 1947 to 2009, as in Bilbao, the coincident sample size) to compute the mean of the summer maxima and the mean of the winter minima and the results remain essentially the same in summer. In winter, although the order is unchanged, the increase in the average winter minima is noticeable in all cases, moving to -3.3°C in Madrid, -0.5°C in Seville and 0.8°C in Valencia. This is consistent with Prieto et al. (2004) who observe an increase in the mean minimum winter temperature across Peninsular Spain. On the other hand, Brunet et al. (2007), also focusing on mainland Spain, point out that the process of warming of the minima is more marked from 1973. From Fig. 2, we note that this pattern seems to be confirmed by minima in summer for Seville

and Valencia. Furthermore, there appears to be an increasing linear trend, to a major or minor extent, in most of the considered series.

We have estimated the model for each of the four considered extreme series and sites with and without the linear trend in the location parameter in order to check if the model that allows the inclusion of a linear time trend fits better than that of the constant mean.

Table 2 shows the estimates of the constant and linear models for $\tilde{\mu}$ in GEV model applied to the extreme temperature series for each of the four considered sites, as well as their corresponding deviance statistics. As indicated in the previous section, according to Almarza (2000), the results for Madrid might be influenced by the urban heat island effect. So, to keep the artificial trend pointed out by Almarza (2000) away from our conclusions, the GEV

Fig. 2 Extreme temperatures in Bilbao (1947–2009), Madrid (1900–2009), Seville (1922–2009) and Valencia (1938–2009). This figure shows the evolution of summer maximum temperatures (Sum_maxt), summer minimum temperatures (Sum_mint), winter maximum temperatures (Win_maxt) and winter minimum temperatures (Win_mint) for Bilbao, Madrid, Seville and Valencia sites, each

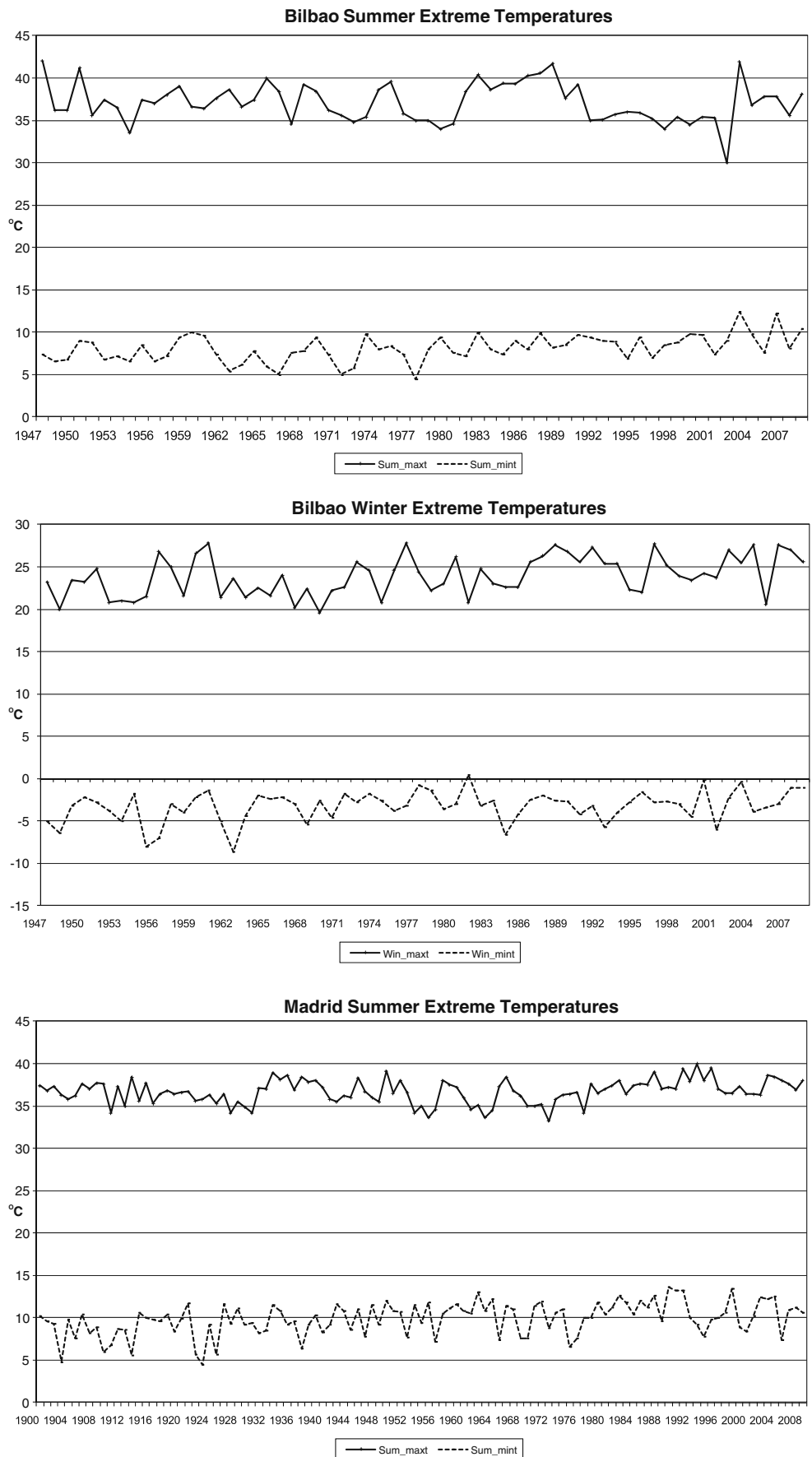


Fig. 2 (continued)

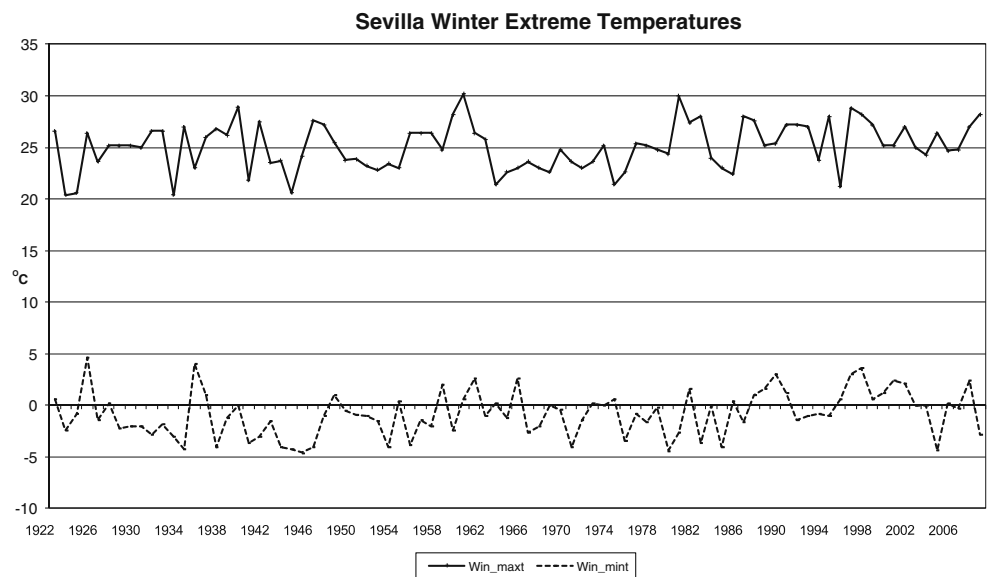
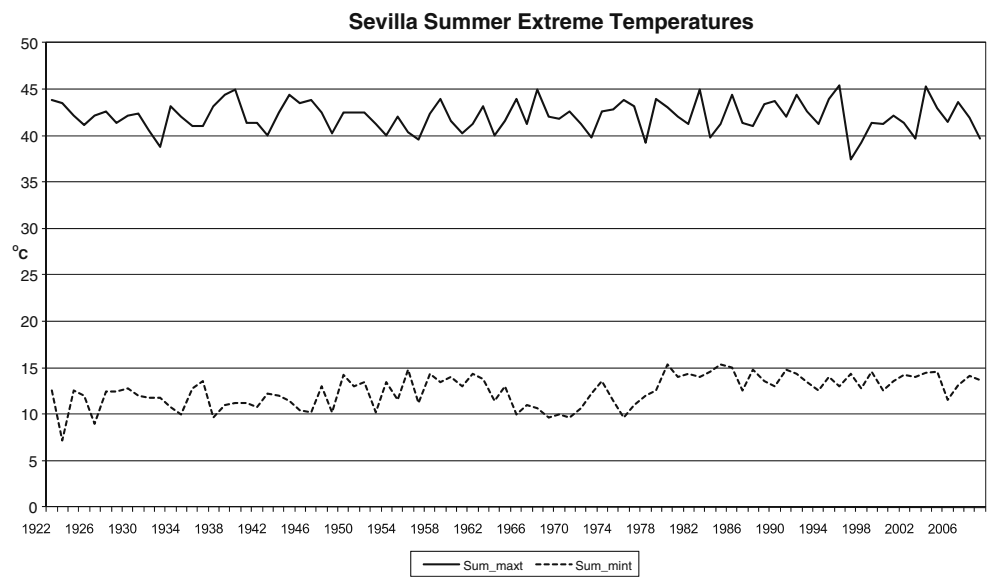
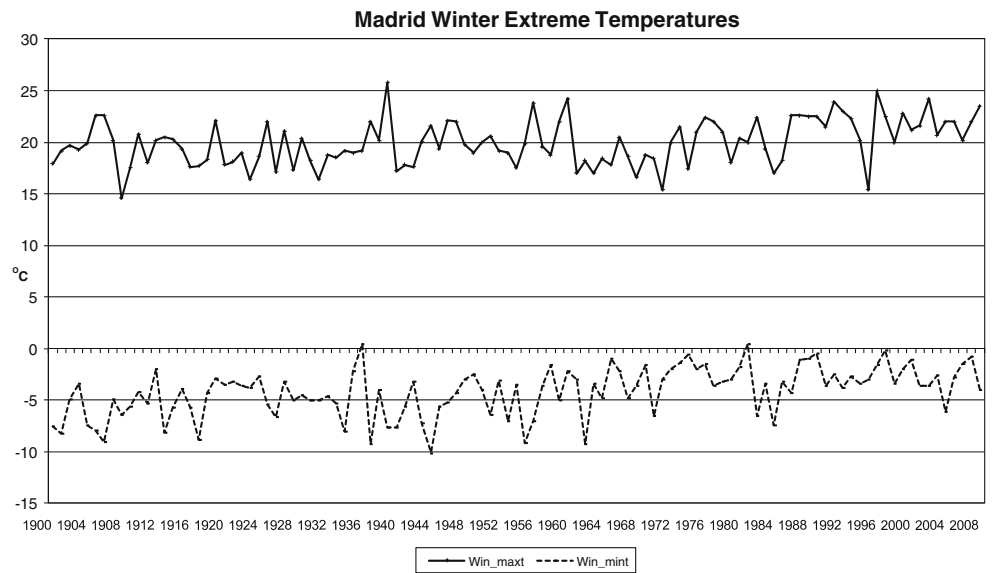
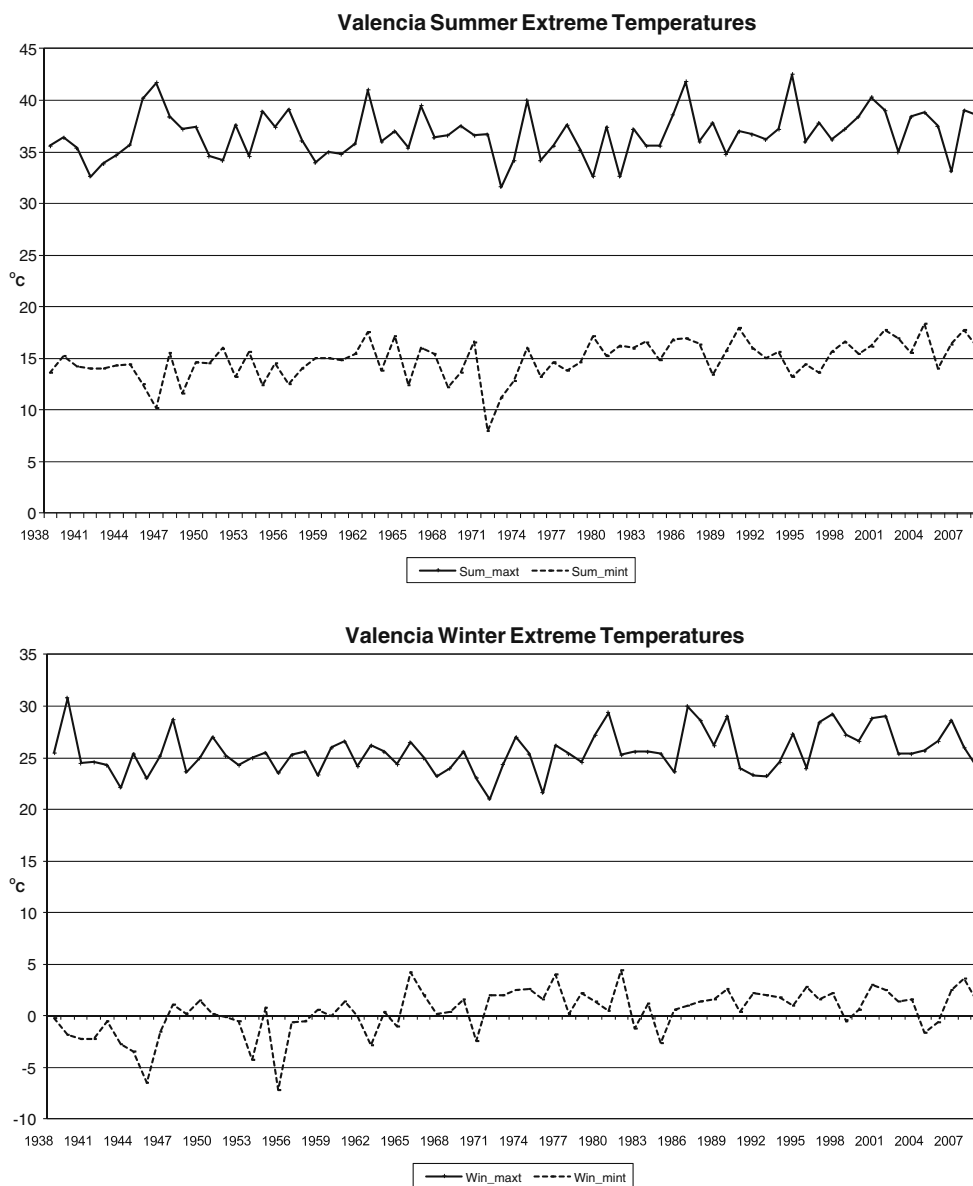


Fig. 2 (continued)



model has been additionally fitted to data for the sample 1960–2009 (see Table 2, panel B2).

Thus, for instance, the GEV model for the winter minima in Bilbao leads to a maximised log-likelihood of -120.94 . Allowing a linear trend in μ , it has a maximised log-likelihood of -118.40 . The deviance statistic for comparing these two models is therefore $D=5.07$, exceeding the critical value from the χ^2 distribution at $\alpha=5\%$, say 3.84. It implies that the linear trend component explains a substantial amount of the variation in the data and, consequently, we select the GEV model with time-varying location parameter. Similar results are obtained when estimating the rest of the extreme temperature series, except for summer maxima in Bilbao, Seville and Valencia, as well as summer and winter minima in Madrid from 1960 onwards, hence implying there is insufficient evidence of a linear trend in them.

The result for Valencia is consistent with that of Miró et al. (2006), in which it is shown that the summer (July and August) minima tended to exhibit a larger thermal increase than the daily averages themselves, while the summer (July and August) maxima displayed no increase in the Valencia region over the period 1958–2003.

From the comparison of estimates for the whole sample (Table 2, panel B1) and the free-of-urban-island-effect sample in Madrid (Table 2, panel B2), the results are mixed. On the one hand, the increasing time trend in maximum temperatures both in summer and winter is confirmed. Furthermore, considering the subsample from 1960 onwards, the estimated rise per decade becomes even greater, moving from 0.1°C (0.2°C) to 0.6°C (0.7°C) in summer (winter). On the other hand, when fitting the GEV model to minimum temperature data, it can be seen that,

Table 2 Parameter estimates of the constant and linear models for μ in GEV model applied to temperature extreme data

	Sum_maxt	Sum_mint	Win_maxt	Win_mint
Panel A: Bilbao (1947–2009)				
Constant model ($\tilde{\mu}, \tilde{\sigma}, \tilde{\xi}$)	(36.29°C, 2.31°C, -0.29)	(8.67°C, 1.60°C, -0.30)	(23.24°C, 2.38°C, -0.38)	(-2.51°C, 1.53°C, -0.09)
Linear model ($\tilde{\beta}_0, \tilde{\beta}_1, \tilde{\sigma}, \tilde{\xi}$)	(36.95°C, 0.02°C, 2.24°C, -0.26)	(7.37°C, 0.04°C, 1.38°C, -0.24)	(21.56°C, 0.05°C, 2.06°C, -0.27)	(-3.34°C, 0.02°C, 1.46°C, -0.09)
Deviance St.	1.75	14.14 (***)	10.80 (***)	5.07 (**)
Panel B1: Madrid (1900–2009)				
Constant model ($\tilde{\mu}, \tilde{\sigma}, \tilde{\xi}$)	(36.21°C, 1.41°C, -0.32)	(10.67°C, 1.69°C, -0.11)	(19.14°C, 2.15°C, -0.24)	(-3.22°C, 2.06°C, -0.13)
Linear model ($\tilde{\beta}_0, \tilde{\beta}_1, \tilde{\sigma}, \tilde{\xi}$)	(35.65°C, 0.01°C, 1.40°C, -0.38)	(9.23°C, 0.02°C, 1.42°C, -0.01)	(17.93°C, 0.02°C, 2.06°C, -0.24)	(-5.18°C, 0.03°C, 1.81°C, -0.12)
Deviance St.	6.49 (**)	25.65 (***)	11.75 (***)	28.95 (***)
Panel B2: Madrid (1960–2009)				
Constant model ($\tilde{\mu}, \tilde{\sigma}, \tilde{\xi}$)	(36.36°C, 1.52°C, -0.35)	(11.33°C, 1.57°C, -0.13)	(19.87°C, 2.54°C, -0.44)	(-2.10°C, 1.50°C, -0.02)
Linear model ($\tilde{\beta}_0, \tilde{\beta}_1, \tilde{\sigma}, \tilde{\xi}$)	(34.89°C, 0.06°C, 1.18°C, -0.26)	(11.05°C, -0.01°C, 1.55°C, -0.12)	(17.94°C, 0.07°C, 2.13°C, -0.28)	(-2.37°C, 0.01°C, 1.49°C, -0.02)
Deviance St.	18.66 (***)	0.47	9.52 (***)	0.42
Panel C: Seville (1922–2009)				
Constant model ($\tilde{\mu}, \tilde{\sigma}, \tilde{\xi}$)	(41.57°C, 1.67°C, -0.36)	(13.23°C, 1.47°C, -0.08)	(23.34°C, 2.27°C, -0.31)	(-0.26°C, 2.32°C, -0.46)
Linear model ($\tilde{\beta}_0, \tilde{\beta}_1, \tilde{\sigma}, \tilde{\xi}$)	(41.49°C, 0.00°C, 1.68°C, -0.36)	(11.79°C, 0.03°C, 1.28°C, -0.09)	(23.46°C, 0.01°C, 2.18°C, -0.29)	(-0.96°C, 0.01°C, 2.21°C, -0.41)
Deviance St.	0.06	24.12 (***)	4.19 (**)	4.04 (**)
Panel D: Valencia (1938–2009)				
Constant model ($\tilde{\mu}, \tilde{\sigma}, \tilde{\xi}$)	(35.85°C, 2.15°C, -0.21)	(15.64°C, 1.62°C, -0.08)	(24.79°C, 1.84°C, -0.17)	(1.38°C, 1.77°C, -0.03)
Linear model ($\tilde{\beta}_0, \tilde{\beta}_1, \tilde{\sigma}, \tilde{\xi}$)	(35.14°C, 0.02°C, 2.12°C, -0.20)	(14.19°C, 0.03°C, 1.37°C, -0.03)	(24.01°C, 0.02°C, 1.80°C, -0.16)	(-0.50°C, 0.04°C, 1.63°C, -0.08)
Deviance St.	2.49	19.21 (***)	4.02 (**)	16.91 (***)

Table 2 shows the estimates of the constant and linear models for $\tilde{\mu}$ in GEV model applied to the series of summer maximum temperature (Sum_maxt), summer minimum temperature (Sum_mint), winter maximum temperature (Win_maxt) and winter minimum temperature (Win_mint) registered at Bilbao, Madrid, Seville and Valencia (sample period in brackets). (**) and (***) denote statistical significance at the 5% and 1%, respectively

according to the likelihood ratio test, the stationary GEV model is preferable to the alternative non-stationary model.

Regarding the rest of the sites, the estimated rise, $\tilde{\beta}_1$, for winter maxima (minima) is 0.1°C (0.1°C) per decade in Seville, 0.2°C (0.4°C) in Valencia, while it is 0.5°C (0.2°C) in Bilbao. The estimated trend for summer minima, which approximates the nighttime temperature, is 0.3°C per decade in Seville and Valencia while it is 0.4°C in Bilbao. Focusing on summer maximum temperatures, as commented previously, we find evidence of a linear trend in only one of the four considered sites, i.e. Madrid, which is consistent with Dankers and Hiederer (2008) who projected for central Spain the greatest increase for the number of days where the maximum temperature exceeds 35°C .

Also note that during the studied samples, summer minimum temperatures have increased while the maximum ones have remained constant in three of the four studied sites, thus decreasing the daily temperature range. This fact is also true for the Valencia observatory series in winter, where minima have increased more than maxima. Additionally, it is useful to notice that in all cases $\tilde{\xi} > -0.5$ is verified, implying that regularity conditions are satisfied.

To judge the accuracy of the model, the probability and the quantile plots are used. Both graphical techniques contain the same information, but on a different scale. They are based on comparisons of the empirical distribution function and the candidate model.

Given an ordered sample of independent observations: $x_{(1)} \leq x_{(2)} \leq \dots \leq x_{(n)}$, from a population with estimated distribution function \hat{F} ,

- a probability plot consists of the points $\left\{ \left(\hat{F}(x_{(i)}), \frac{i}{n+1} \right) : i = 1, \dots, n \right\}$,
- a quantile plot consists of the points $\left\{ \left(\hat{F}^{-1} \left(\frac{i}{n+1} \right), x_{(i)} \right) : i = 1, \dots, n \right\}$.

If \hat{F} is a reasonable model for the population distribution, the points of both the probability plot and the quantile plot should lie close to the unit diagonal. Thus, the accuracy of the model is judged in terms of its agreement with the data that were actually used to estimate it.

The diagnostic plots for the selected models are shown in Figs. 3, 4, 5, 6. Most of the plotted points showed by the probability and the quantile plots are near-linear, which is indicative of the validity of the fitted model. However, the

Fig. 3 Diagnostic plots of GEV fit to extreme temperatures in Bilbao (1947–2009). This figure shows the probability plot (PP) and the quantile plot (QP) of GEV fit to the series of summer maximum temperatures (Sum_maxt), winter maximum temperatures (Win_maxt) and the sign-changed series of summer minimum temperatures (-Sum_mint) and winter minimum temperatures (-Win_mint)

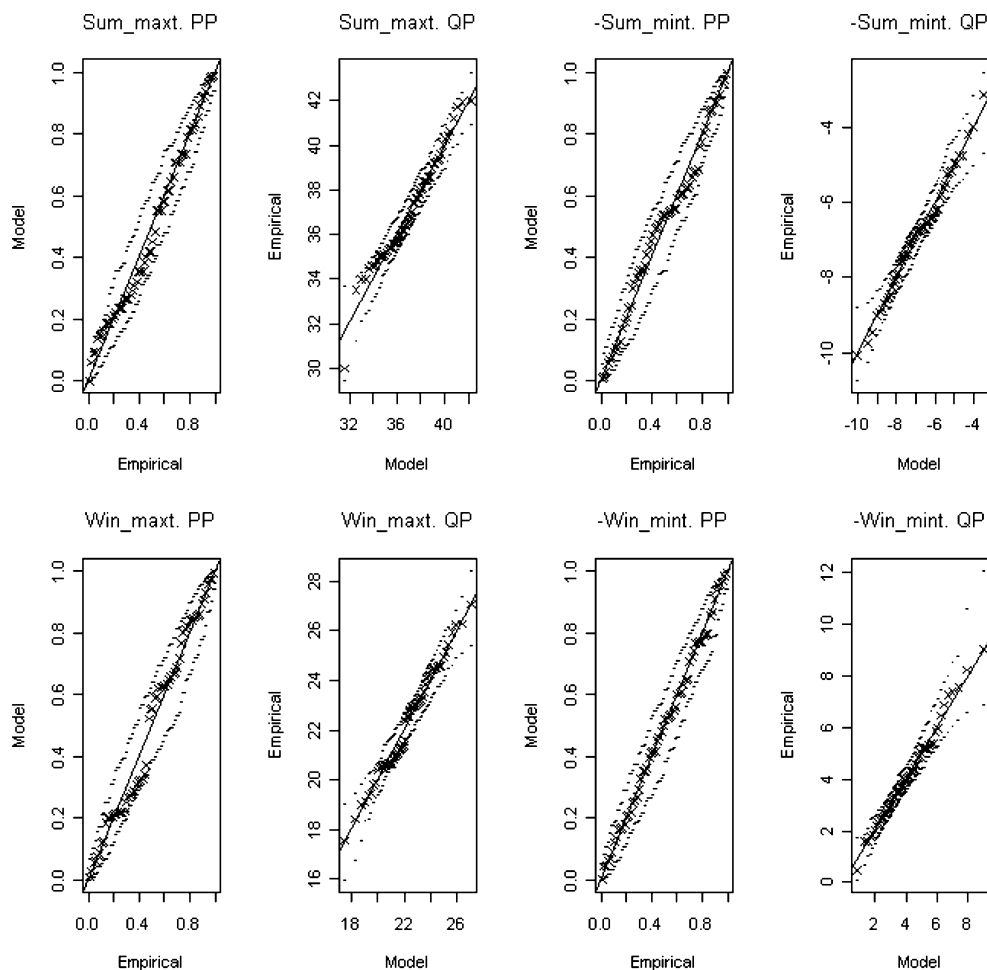


Fig. 4 **a** Diagnostic plots of GEV fit to extreme temperatures in Madrid (1900–2009). This figure shows the probability plot (PP) and the quantile plot (QP) of GEV fit to the series of summer maximum temperatures (Sum_maxt), winter maximum temperatures (Win_maxt) and the sign-changed series of summer minimum temperatures (-Sum_mint) and winter minimum temperatures (-Win_mint). **b** Diagnostic plots of GEV fit to extreme temperatures in Madrid (1960–2009). This figure shows the probability plot (PP) and the quantile plot (QP) of GEV fit to the series of summer maximum temperatures (Sum_maxt), winter maximum temperatures (Win_maxt) and the sign-changed series of summer minimum temperatures (-Sum_mint) and winter minimum temperatures (-Win_mint)

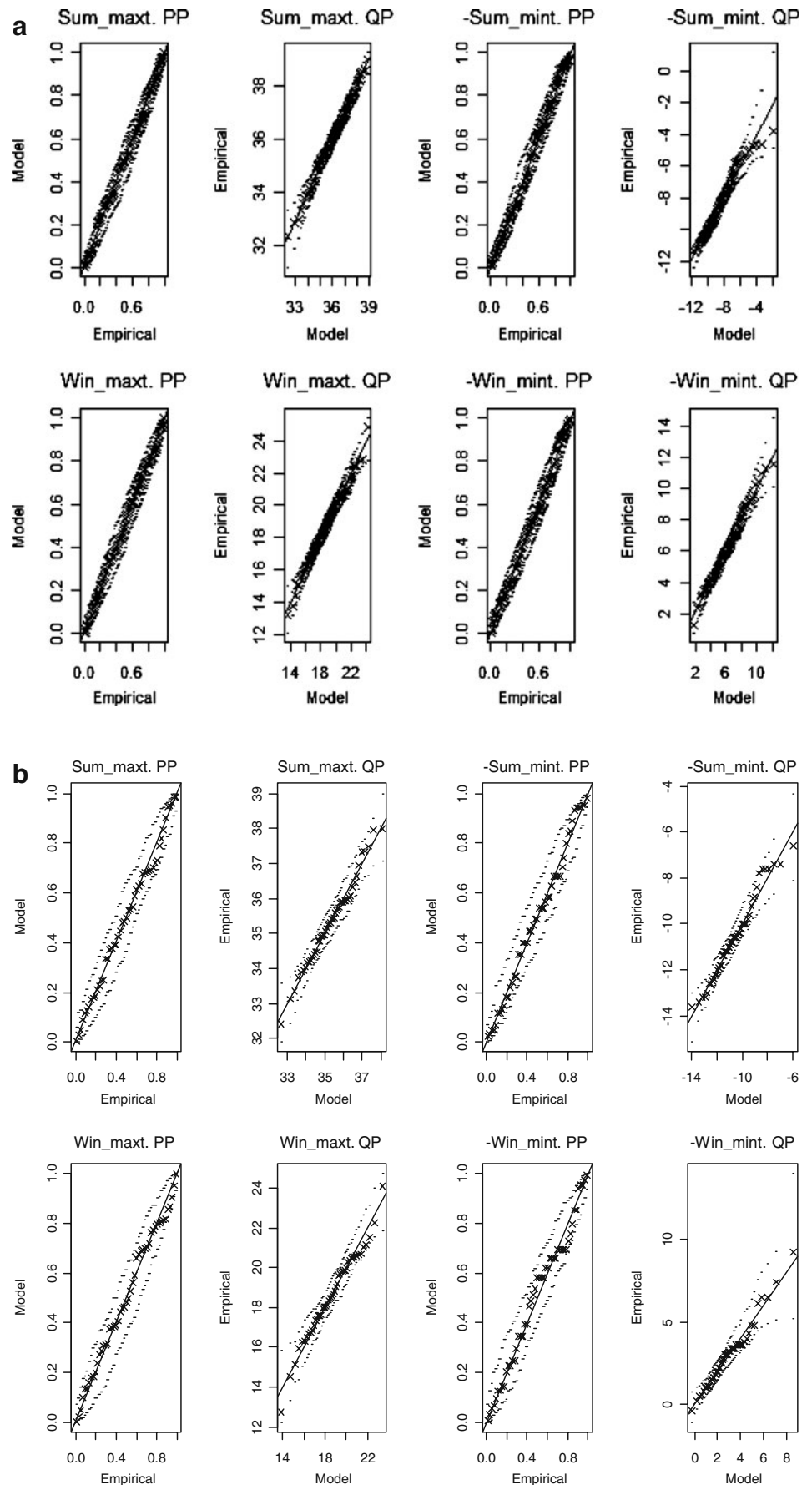
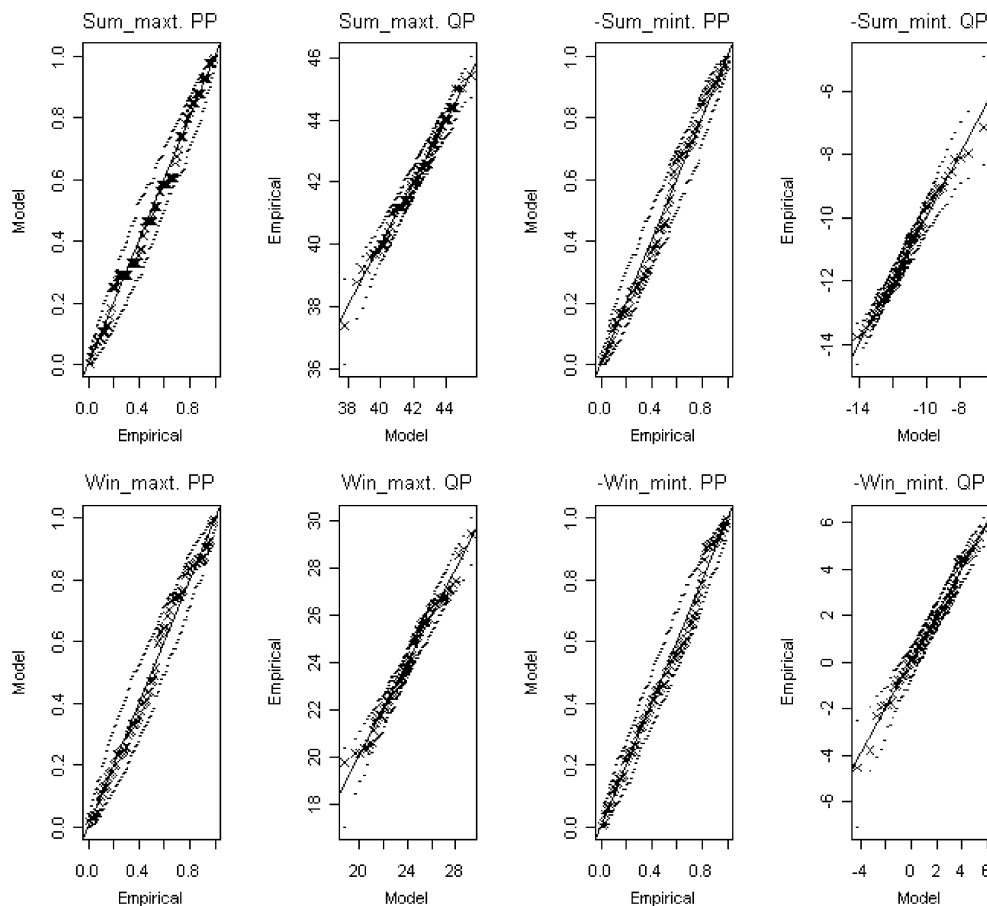


Fig. 5 Diagnostic plots of GEV fit to extreme temperatures in Seville (1922–2009). This figure shows the probability plot (PP) and the quantile plot (QP) of GEV fit to the series of summer maximum temperatures (Sum_maxt), winter maximum temperatures (Win_maxt) and the sign-changed series of summer minimum temperatures (-Sum_mint) and winter minimum temperatures (-Win_mint)



series of summer maxima in Bilbao and summer minima in Madrid exhibit higher discrepancies, possibly indicating departures of the observations from the theoretical model at the tails of the distributions.

The estimation results enable us to obtain the probability of exceeding (not surpassing) certain levels of temperature for each of the considered extreme series according to different time horizons. Alternatively, we can estimate the exceeded (not surpassed) temperature level with a fixed probability.

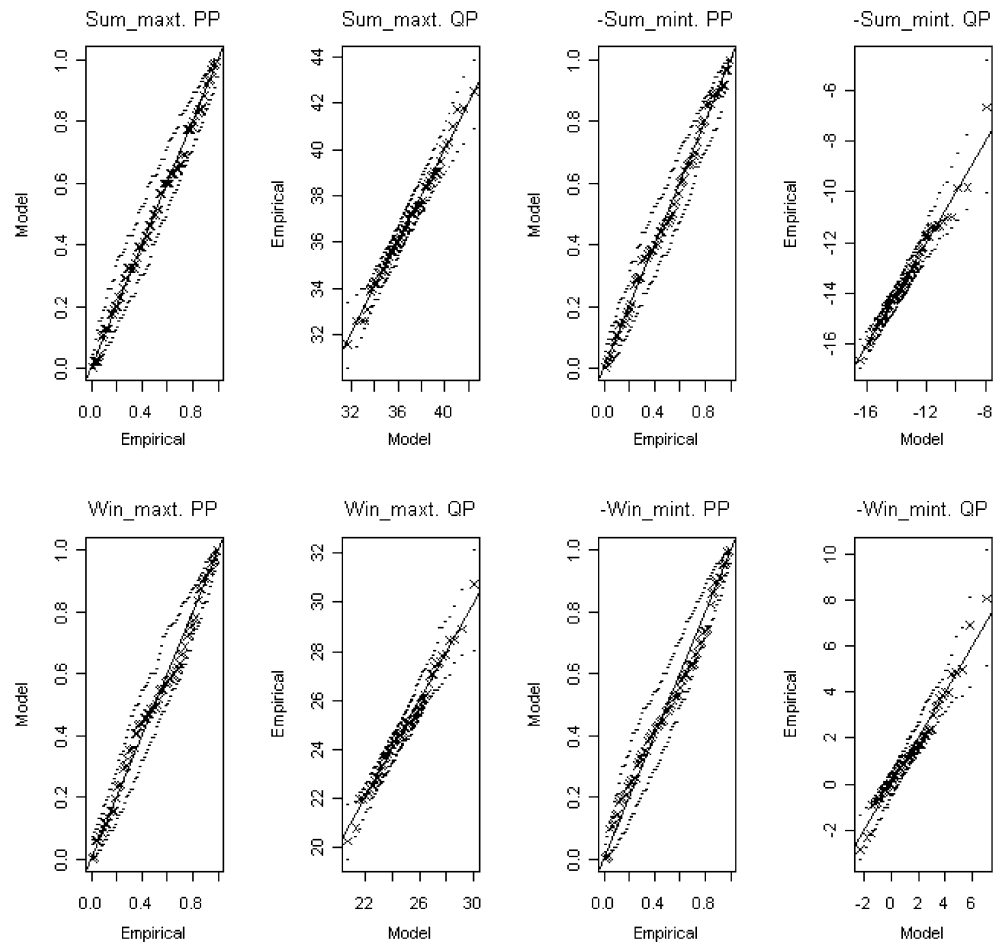
Table 3 shows the estimated maximum (minimum) exceeded (not surpassed) temperature levels, together with 95% confidence intervals (°C) calculated from the profile-likelihood methods, with different probabilities in several time horizons for each of the considered seasons and sites. Thus, by extrapolating the observed trends towards the future, the maximum temperature in summer in Madrid is expected to exceed 37.3°C, 39.1°C and 40.6°C in 2020, 2050 and 2075, respectively, with a probability of 90%, while the minimum temperature in winter in Bilbao is expected to be below -0.3°C, 0.4°C and 1.0°C in the above mentioned years. Similarly, with a probability of 50%, the maximum temperature in winter is expected to exceed 26.1°C, 26.7°C and 27.2°C in 2020, 2050 and 2075,

respectively, in Seville; while with the same probability (50%), the minimum temperature in summer is expected to be below 16.8°C, 18.0°C and 18.9°C in Valencia. It should be noted that confidence intervals are generally quite wide and become wider with prediction time, reflecting the inherent uncertainty associated with making inference beyond the sample range.

5 Conclusions

In view of the number of previous research studies showing overall increased temperatures over the coming decades, together with an increase in magnitude and frequency of extreme temperature events, the analysis of the tails of the distributions of the summer temperature maxima and winter temperature minima becomes of particular concern. In fact, the impacts of a gradual increase in maximum temperatures in summer combined with some sort of persistence are expected to lead to undesirable consequences including increased population mortality (especially among high-risk groups like the elderly), reduction in productivity and efficiency, droughts, increased severity of forest fires, increase and change in occurrence of pests, direct damage

Fig. 6 Diagnostic plots of GEV fit to extreme temperatures in Valencia (1938–2009). This figure shows the probability plot (PP) and the quantile plot (QP) of GEV fit to the series of summer maximum temperatures (Sum_maxt), winter maximum temperatures (Win_maxt) and the sign-changed series of summer minimum temperatures (-Sum_mint) and winter minimum temperatures (-Win_mint)



to vegetation, electrical power and water supply cuts or reduced discharge in many rivers, among others.

Moreover, this work extends the analysis to the series of summer temperature minima and winter temperature maxima, since an overall increase in these extreme events may entail not only positive consequences because of the less severe (extreme) winter (summer) conditions, but also negative economic impacts, for instance on mainly seasonal activities such as heating/cooling equipment production, clothing and textile production, tourism, etc.

Within the framework of expected changing climate conditions, the aim of the present study is to analyse extreme temperatures in four climate-differentiated sites across Peninsular Spain. From visual inspection of the temperature extreme series, there appears to be a generally increasing trend over the sample periods. Conventional extreme value models that assume stationarity would be inappropriate for non-stationarity processes which present time-varying means, as has turned out to be the case for most of the extreme series involved in the present study. Consequently, we apply the extreme value theory, by fitting the non-stationary GEV distribution to the extreme temperature records from four observatories located in El Retiro

Park (Madrid) and in the airports of Bilbao, Seville and Valencia.

Our findings do show that, for most of the considered series, there is statistical evidence of a time trend that should be taken into account and may be explained by long-term climate changes. Particularly in winter, both maxima and minima have been rising at a rate from 0.1°C to 0.7°C per decade in all the studied sites, with the only exception being Madrid, where results indicate that minima have remained constant over the free-of-urban-heat-island period (i.e., 1960–2009). In summer, minima for Bilbao, Seville and Valencia show an increasing trend over time varying from 0.3°C to 0.4°C, whereas maxima only exhibit a similar pattern in Madrid, increasing 0.06°C per decade.

These results allow us to conclude that, except for Madrid, during the cold season, temperature maxima (minima) are becoming more (less) extreme, leading to less severe winters. In summer, only the minima are shown to have been increasing with time. With regards to Madrid records, focusing on the sample period from 1960 to 2009, it can be concluded that extreme temperatures are becoming more extreme in summer and that winter maxima present an increasing trend over time, too.

Table 3 Estimated maximum (minimum) temperature level [and 95% confidence interval, the considered seasons (winter and summer) and sites (Bilbao 1947–2009, Madrid 1960–2009, calculated from the profile-likelihood methods) to be exceeded (to be below) with a fixed Seville 1922–2009 and Valencia 1938–2009) probability (90%, 70% and 50%) in different time horizons (2020, 2050 and 2075) for each of

Year (Prob)	Bilbao			Madrid		
	90%	70%	50%	90%	70%	50%
Panel A: Estimated summer maximum temperature level [and 95% confidence interval] (°C) to be exceeded with a determined probability						
2020	34.1 [33.6, 34.3]	35.8 [35.2, 36.3]	37.1 [36.3, 37.9]	37.3 [35.3, 39.3]	38.2 [36.1, 40.3]	38.8 [36.6, 41.1]
2050	34.1 [33.6, 34.3]	35.8 [35.2, 36.3]	37.1 [36.3, 37.9]	39.1 [36.3, 41.8]	40.0 [37.1, 42.8]	40.6 [37.6, 43.6]
2075	34.1 [33.6, 34.3]	35.8 [35.2, 36.3]	37.1 [36.3, 37.9]	40.6 [37.2, 43.9]	41.5 [38.0, 44.9]	42.1 [38.5, 45.7]
Panel B: Estimated summer minimum temperature level [and 95% confidence interval] (°C) to be reached with a determined probability						
2020	11.6 [9.6, 13.6]	10.6 [8.4, 12.7]	9.8 [7.5, 12.1]	12.5 [12.4, 13.0]	11.6 [11.1, 12.0]	10.7 [10.0, 11.3]
2050	12.8 [10.2, 15.4]	11.8 [9.1, 14.5]	11.0 [8.1, 13.9]	12.5 [12.4, 13.0]	11.6 [11.1, 12.0]	10.7 [10.0, 11.3]
2075	13.8 [10.7, 16.9]	12.8 [9.6, 16.0]	12.0 [8.6, 15.4]	12.5 [12.4, 13.0]	11.6 [11.1, 12.0]	10.7 [10.0, 11.3]
Panel C: Estimated winter maximum temperature level [and 95% confidence interval] (°C) to be exceeded with a determined probability						
2020	23.3 [20.2, 26.4]	24.9 [21.6, 28.1]	26.0 [22.5, 29.6]	20.3 [16.3, 24.1]	21.9 [17.7, 26.0]	23.1 [18.7, 27.5]
2050	24.9 [20.9, 28.8]	26.4 [22.3, 30.6]	27.5 [23.2, 32.0]	22.5 [17.1, 27.7]	24.1 [18.5, 29.6]	25.3 [19.5, 31.1]
2075	26.2 [21.4, 30.9]	27.7 [22.8, 32.6]	28.8 [23.7, 34.0]	24.4 [17.7, 30.7]	26.0 [19.2, 32.6]	27.1 [20.1, 34.1]
Panel D: Estimated winter minimum temperature level and [95% confidence interval] (°C) to be reached with a determined probability						
2020	-0.3 [-2.4, 2.0]	-1.2 [-3.5, 1.1]	-2.0 [-4.5, 0.5]	-0.8 [-1.1, -0.5]	-1.8 [-2.2, -1.4]	-2.6 [-3.3, -2.0]
2050	0.4 [-2.3, 3.5]	-0.4 [-3.4, 2.6]	-1.2 [-4.4, 1.9]	-0.8 [-1.1, -0.5]	-1.8 [-2.2, -1.4]	-2.6 [-3.3, -2.0]
2075	1.0 [-2.2, 4.7]	0.1 [-3.3, 3.8]	-0.6 [-4.3, 3.1]	-0.8 [-1.1, -0.5]	-1.8 [-2.2, -1.4]	-2.6 [-3.3, -2.0]
Valencia						
Panel A: Estimated summer maximum temperature level [and 95% confidence interval] (°C) to be exceeded with a determined probability						
2020	39.9 [39.6, 40.1]	41.2 [40.8, 41.5]	42.1 [41.6, 42.6]	33.8 [33.5, 34.1]	35.4 [34.9, 35.9]	36.6 [35.9, 37.3]
2050	39.9 [39.6, 40.1]	41.2 [40.8, 41.5]	42.1 [41.6, 42.6]	33.8 [33.5, 34.1]	35.4 [34.9, 35.9]	36.6 [35.9, 37.3]
2075	39.9 [39.6, 40.1]	41.2 [40.8, 41.5]	42.1 [41.6, 42.6]	33.8 [33.5, 34.1]	35.4 [34.9, 35.9]	36.6 [35.9, 37.3]
Panel B: Estimated summer minimum temperature level [and 95% confidence interval] (°C) to be reached with a determined probability						
2020	15.8 [14.2, 17.5]	15.0 [13.2, 16.7]	14.3 [12.4, 16.1]	18.5 [16.6, 20.4]	17.6 [15.6, 19.6]	16.8 [14.7, 18.9]
2050	16.8 [14.8, 18.8]	15.9 [13.8, 18.0]	15.2 [12.9, 17.4]	19.6 [17.3, 22.0]	18.7 [16.3, 21.2]	18.0 [15.4, 20.6]
2075	17.5 [15.2, 19.9]	16.6 [14.3, 19.1]	15.9 [13.4, 18.5]	20.6 [17.9, 23.4]	19.7 [16.9, 22.6]	18.9 [15.9, 22.0]
Panel C: Estimated winter maximum temperature level [and 95% confidence interval] (°C) to be exceeded with a determined probability						
2020	23.3 [20.6, 25.9]	24.9 [22.1, 27.7]	26.1 [23.1, 29.1]	24.2 [21.6, 26.7]	25.5 [22.8, 28.1]	26.4 [23.6, 29.3]
2050	23.9 [20.7, 27.1]	25.5 [22.2, 28.9]	26.7 [23.1, 30.3]	24.9 [21.6, 28.0]	26.1 [22.8, 29.4]	27.1 [23.6, 30.6]
2075	24.4 [20.7, 28.0]	26.0 [22.2, 29.8]	27.2 [23.2, 31.3]	25.4 [21.7, 29.1]	26.7 [22.8, 30.6]	27.7 [23.6, 31.8]
Panel D: Estimated winter minimum temperature level and [95% confidence interval] (°C) to be reached with a determined probability						
2020	2.8 [0.2, 5.3]	1.1 [-1.3, 3.6]	0.0 [-2.5, 2.6]	4.8 [2.3, 7.3]	3.7 [1.0, 6.4]	2.8 [0.0, 5.6]
2050	3.4 [0.2, 6.3]	1.6 [-1.3, 4.7]	0.4 [-2.5, 3.7]	6.2 [3.0, 9.4]	5.1 [1.8, 8.4]	4.2 [0.7, 7.7]
2075	3.8 [0.2, 7.2]	2.0 [-1.3, 5.5]	0.8 [-2.5, 4.5]	7.4 [3.7, 11.2]	6.3 [2.4, 10.0]	5.4 [1.4, 9.4]

Another conclusion is that, in general terms, the daily temperature range has been decreasing over the twentieth century. Also, an estimation of the GEV model allows us to obtain by extrapolation the exceeded (not reached) temperature level related to a fixed probability. For instance with a probability of 90% (50%), the summer maximum temperature is expected to exceed 34.1°C (37.1°C), 39.1°C (40.6°C), 39.9°C (42.1°C) and 33.8°C (36.6°C) in 2050 in Bilbao, Madrid, Seville and Valencia, respectively, while the winter minimum temperature is expected to be below 0.4°C (−1.2°C), −0.8°C (−2.6°C), 3.4°C (0.4°C) and 6.2°C (4.2°C), in 2050, at the above mentioned sites.

Finally, the presented results could be complemented with those from other approaches, with the peak over threshold method being the natural extension of the present work. Furthermore, together with the extrapolation beyond the range of observations shown in this study, other approaches to assessing changes in extreme weather conditions are general circulation models and regional climate models (Beniston et al. 2007; Dankers and Hiederer 2008; Parey 2008).

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