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Evolution of the threshold temperature definition of a heat wave vs. evolution of the minimum mortality temperature: a case study in Spain during the 1983–2018 period

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Abstract

Background: An area of current study concerns analysis of the possible adaptation of the population to heat, based on the temporal evolution of the minimum mortality temperature (MMT). It is important to know how is the evolution of the threshold temperatures (Tthreshold) due to these temperatures provide the basis for the activation of public health prevention plans against high temperatures. The objective of this study was to analyze the temporal evolution of threshold temperatures (Tthreshold) produced in different Spanish regions during the 1983–2018 period and to compare this evolution with the evolution of MMT. The dependent variable used was the raw rate of daily mortality due to natural causes ICD X: (A00-R99) for the considered period. The independent variable was maximum daily temperature (Tmax) during the summer months registered in the reference observatory of each region. Threshold values were determined using dispersion diagrams (annual) of the prewhitened series of mortality temperatures and Tmax. Later, linear fit models were carried out between the different values of Tthreshold throughout the study period, which permitted detecting the annual rate of change in Tthreshold.

Results: The results obtained show that, on average, Tthreshold has increased at a rate of 0.57 ºC/decade in Spain, while Tmax temperatures in the summer have increased at a rate of 0.41 ºC/decade, suggesting adaptation to heat. This rate of evolution presents important geographic heterogeneity. Also, the rate of evolution of Tthreshold was similar to what was detected for MMT.

Conclusions: The temporal evolution of the series of both temperature measures can be used as indicators of population adaptation to heat. The temporal evolution of Tthreshold has important geographic variation, probably related to sociodemographic and economic factors, that should be studied at the local level.

Keywords: Temperature threshold, Minimum mortality temperature, Adaptation, Mortality attributable

Introduction

In recent years, studies in different countries have observed a decrease in the mortality attributable to heat waves [2, 3, 9, 27, 28]. This could be interpreted as a progressive process of population adaptation to high temperatures, due to a variety of factors [19, 31], among which the efficiency of heat prevention plans in different countries is worth mentioning [12].

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The decrease in the impact of heat is generally measured in terms of the decrease in the relative risks of daily mortality associated with extremely hot temperatures. This process can be visualized as an evolution over time towards higher values for the temperature thresholds for heat waves (Tthreshold) [18, 30] (Díaz et al. 2019). The threshold temperature for a heat wave can be generally defined as the epidemiological threshold at which the effects of heat begin to provoke excess mortality attributable to heat. These thresholds also mark the activation of prevention plans based on public health action to respond to high temperatures. These Tthreshold values are dynamic, they vary in time as the as well as the sociodemographic and economic dynamics also makes it. The Tthreshold values can be used as an indicator of the adaptation to extremely high temperatures [18, 30] (Díaz et al. 2019). From the point of view of population adaptation to heat waves, adaptation is complete when the rate of increase in maximum daily temperature as a consequence of global warming is less than the rate of increase in Tthreshold (Díaz et al. 2019) [15], not including summer mortality excesses.

In order to analyze whether a process of population adaptation is in fact occurring, there is research that investigates the evolution of another epidemiological indicator that defines the traditional functional relationship that exists, in the "V" form, between daily mortality and temperature. This indicator is known as minimum mortality temperature (MMT) [2, 8, 33].

The evolution of MMT has also been used as an indicator of possible population adaptation to heat [15, 16]. From a conceptual point of view, MMT and Tthreshold represent two different indicators. In a graphic representation (Fig. 1) of the temperature–mortality relationship, MMT represents the temperature at which mortality reaches its minimum value. Thus, mortality attributable to heat is represented to the right of MMT, while mortality attributable to cold is represented to the left [1]. However, Tthreshold values represent the temperature at which mortality begins to increase due to heat waves. It is evident that mortality due to heat includes mortality due to heat waves [29], however, the behavior and temporal evolution are not necessarily similar.

In the report "Heat Health in the WHO European Region: Updated Evidence for Effective Prevention" [34], the WHO established that the activation of prevention plans to address high temperatures should have an epidemiological basis. That is to say, they should be based on a determination of Tthreshold for each geographic and sub-climatic area of study, based on the increase in mortality with high temperatures. Also, these plans should be revised periodically, given that Tthreshold varies across time. Despite the important role of Tthreshold in the process of population adaptation to high temperatures, there are few studies that analyze its temporal evolution and that also establish variation in time as an indicator of the process of population adaptation to heat waves.

The first objective of this study was to analyze the temporal evolution of Tthreshold temperatures across a period of 36 years (1983–2018) in Spanish regions that are representative of the different impacts of heat waves, and to evaluate whether Tthreshold constitutes a good indicator of population adaptation to high temperatures. Second, this study aimed to compare the rate of evolution of Tthreshold with the rate of evolution observed in MMT during the same

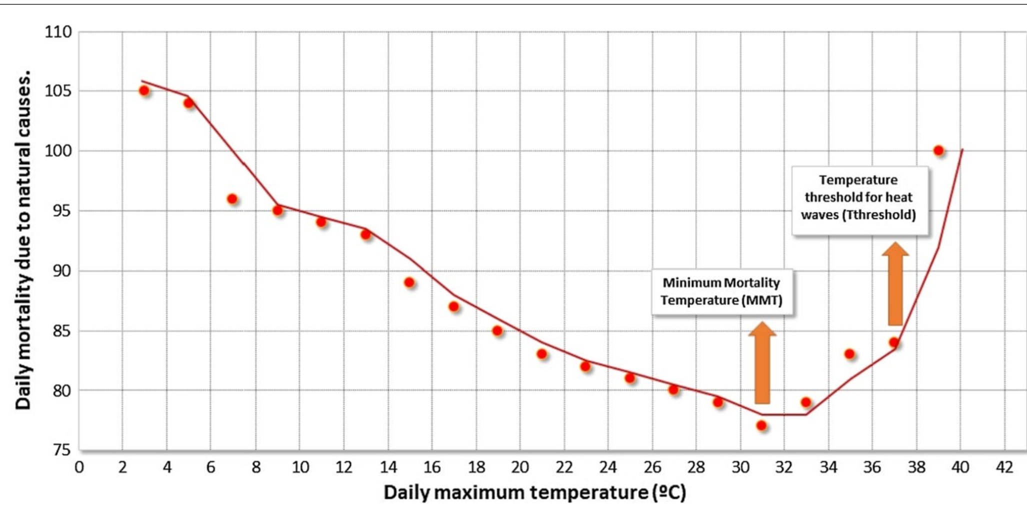

Fig. 1 Temperature–mortality relationship in Madrid, 1983–2018 period. Minimum mortality temperature (MMT) and temperature threshold for heat waves (Tthreshold)

time period studied, to analyze the possible relationship and possible implications for future adaptation.

Materials and methods

Mortality rates

From among all Spanish provinces, 10 were selected as representative of the behavior of Spanish regions in terms of thermal extremes, according to previous studies [9, 11, 32].

The dependent variable was made up of the rate of daily mortality due to natural causes (ICD X: A00-R99) in municipalities with over 10,000 inhabitants in selected Spanish regions during the 1983–2018 period. These data were provided by the National Statistics Institute (INE). Based on daily mortality data, and using population data also supplied by INE, the rate of daily mortality per 100,000 inhabitants was calculated.

Temperature data

The data were provided by the State Meteorological Agency (AEMET). Maximum daily temperature in the summer months (Tmax) was the independent variable, registered in the meteorological observatory of reference in each region during the analyzed period corresponding to 1983–2018.

Tmax was used, because it is the variable that presents the best statistical association with daily mortality during heat waves [11, 18].

In addition, we used the rate of evolution of maximum daily temperature (Tmax) in the summer months for the 1983–2018 period and for future Tmax foreseen for the 2051–2100 time horizon under an RCP8.5 emissions scenario. Data were taken from previous papers: [16] and Díaz et al. 2019, respectively.

Determination of threshold temperatures (Tthreshold)

In order to eliminate the analogous components of trend, seasonality and autoregressive character in the series of temperature and mortality, we used a pre-whitening procedure with the Box–Jenkins' methodology [4].

These prewhitened series constitute the residuals obtained through ARIMA modeling and represent the anomalies that correspond to the mortality rate. The series was modeled for the entire 1983–2018 period.

Find below the equation of the ARIMA regression model in the general form:

$$Y_t = b + \beta_{1p}\varphi_{pt} + \beta_{2q}\theta_{qt} + \beta_{3P}s\varphi_{Pt} + \beta_{4Q}s\theta_{Qt} + \beta_5 n1_t + \beta_{6\alpha}\cos(\alpha t) + \beta_{7\alpha}\mathrm{sen}(\alpha t) + \varepsilon_t,$$
$$\varepsilon_t \sim N(0, \sigma),$$

where Y_t is mortality on day t; b is the intercept; β are the coefficient of each variable in each case; φ is the non-seasonal autoregressive parameter of order p on day t; θ is the non-seasonal mobile average of order q on day t; $s\varphi$ is the seasonal autoregressive parameter of order P on day t;$s\theta_{Qt}$ is the seasonal mobile average of order Q on day t; n1 is the trend on day t; cos $(\alpha t)$and sin (αt) are seasonal functions of α {365, 180, 120, 90, 60, 30} periods on day t; and ε is the residuals which performs a normal distribution of mean = 0, and σ is the standard deviation of the ε. Since trend was included as an independent variable, the integrated parameter was $I = 0$. Lastly, it were fixed a period of 7 days for seasonal part of the regression model.

Later, for each year, a dispersion diagram (scatter plot) was constructed such that the X-axis represents maximum daily temperatures in 2 °C intervals, and the Y-axis represents the value corresponding to these residuals, averaged for these intervals, with the corresponding confidence intervals. Using this methodology, it was possible to relate statistically significant mortality anomalies that were detected at a determined temperature. The value of Tmax, the point at which mortality increases in an anomalous way, was denominated Tthreshold. This methodology has been used in multiple other studies [6, 7, 11, 23, 30].

By way of example, Fig. 2 shows the process by which residuals were obtained and the later determination of Tthreshold in the case of Barcelona for the 1983–2018 period.

Calculation of the rate of temporal evolution of Tthreshold

Once Tthreshold was calculated for each year and region, a linear fit process was carried out for the results obtained. The values on the X-axis represent the years between 1983 and 2018, and the Y-axis show the values of Tthreshold for each year, when it was possible to calculate this value. The slope of the line obtained in the linear fit model represents the rate of evolution of Tthreshold during the period of analysis.

Comparison with the evolution of MMT

In other recent studies in Spain for the same period (1983–2018), the rate of evolution of MMT was calculated [16]. If both rates are compared and bivariate correlations are established between the annual series of Tthreshold and MMT during the study period, it is possible to describe a potential association between them.

Also, cross-correlation functions (CCF) were calculated between the series, which allowed for the analysis of a possible time lag between the values of MMT and Tthreshold.

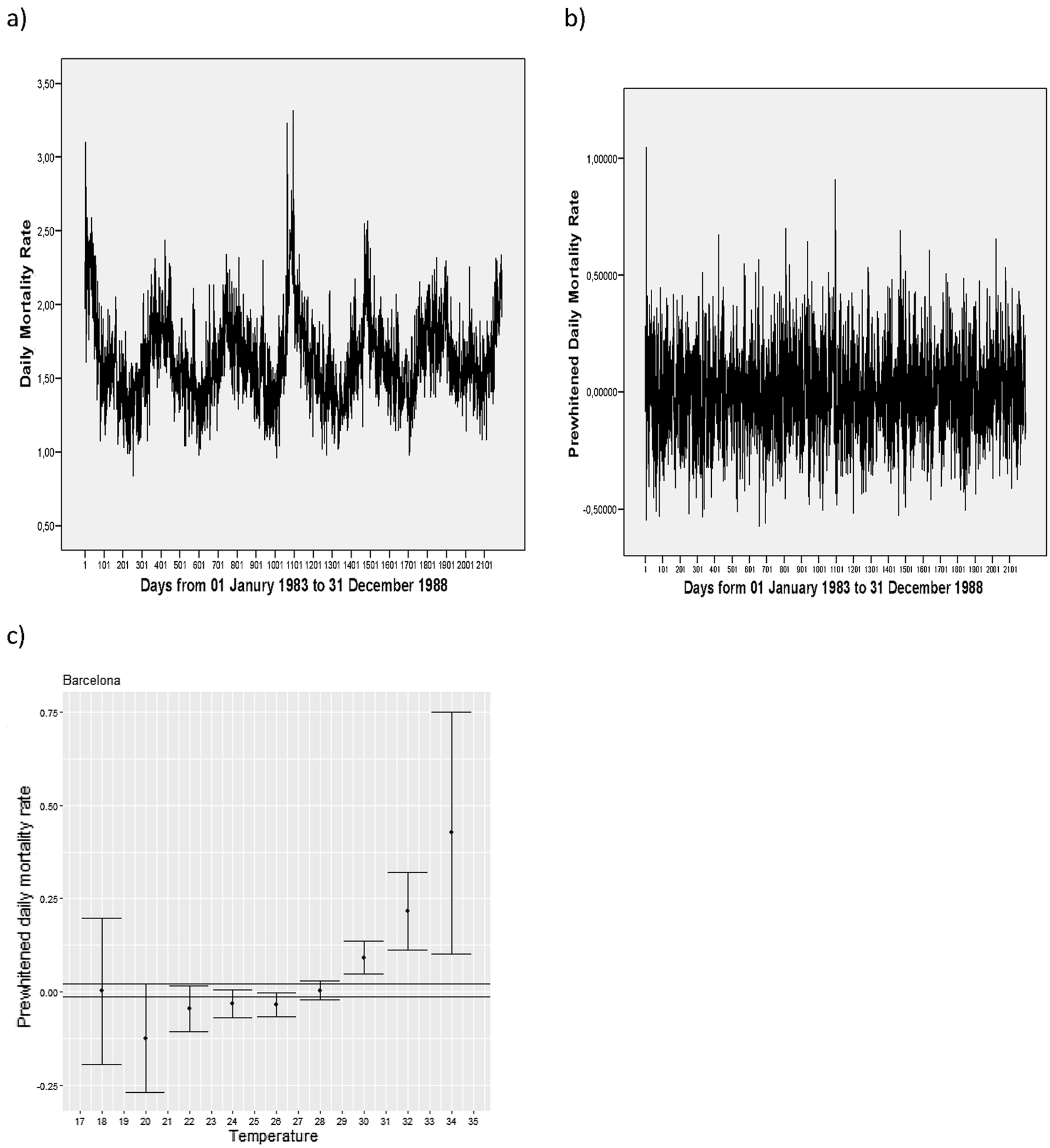

Fig. 2 **a** Temporal evolution of the daily mortality rate for Barcelona during the 1983–2018 period; **b** temporal evolution of the daily mortality rate prewhitened series for this period, and **c** graphic illustration of the threshold temperature for the 1983–1988 period

Determination of the increase in Tthreshold

Given that we were working with spatial data, the time evolution of the results was analyzed using a linear mixed model (link = identity). In this model, the Tthreshold values were used, calculated as a dependent variable, the independent variable of fixed effects was the year, and region was used as a factor of random effects, by way of the following equation:

$$\text{geeglm}\left(\text{formula} = \text{d\$Tumbral} \sim \text{d\$year, data} = \text{data, id} = \text{d\$Provincia}\right).$$

This analysis was carried out using the statistical software package SPSS 27. The linear mixed models used the geeglm() function of the geepack package of free R software.

Results

Figure 3 shows the graphs that correspond to the linear fit models for Tthreshold, for the total of the 10 regions analyzed. As can be observed, in all of the cases except Badajoz, there was an increasing temporal evolution in terms of the slopes of all of the fit lines.

Table 1 shows the average values that correspond to the daily mortality rate and the maximum daily temperature (Tmax) for the summer months in different Spanish regions for the 1983–2018 period. It also shows the average values of the rate of change in the minimum mortality temperatures (MMT) obtained previously [16] and the average values of threshold temperatures (Tthreshold) corresponding to the linear fit models shown in Fig. 3. The values of the slopes are expressed in terms of °C/decade, both in the case of Tthreshold as well as for the values of MMT. Table 1 also shows the Pearson correlation coefficients of the bivariate correlations obtained between the series of the annual values of Tthreshold and MMT. In general, no correlation exists between the series, except in three regions (Alicante, Barcelona and Zaragoza), and in three of the

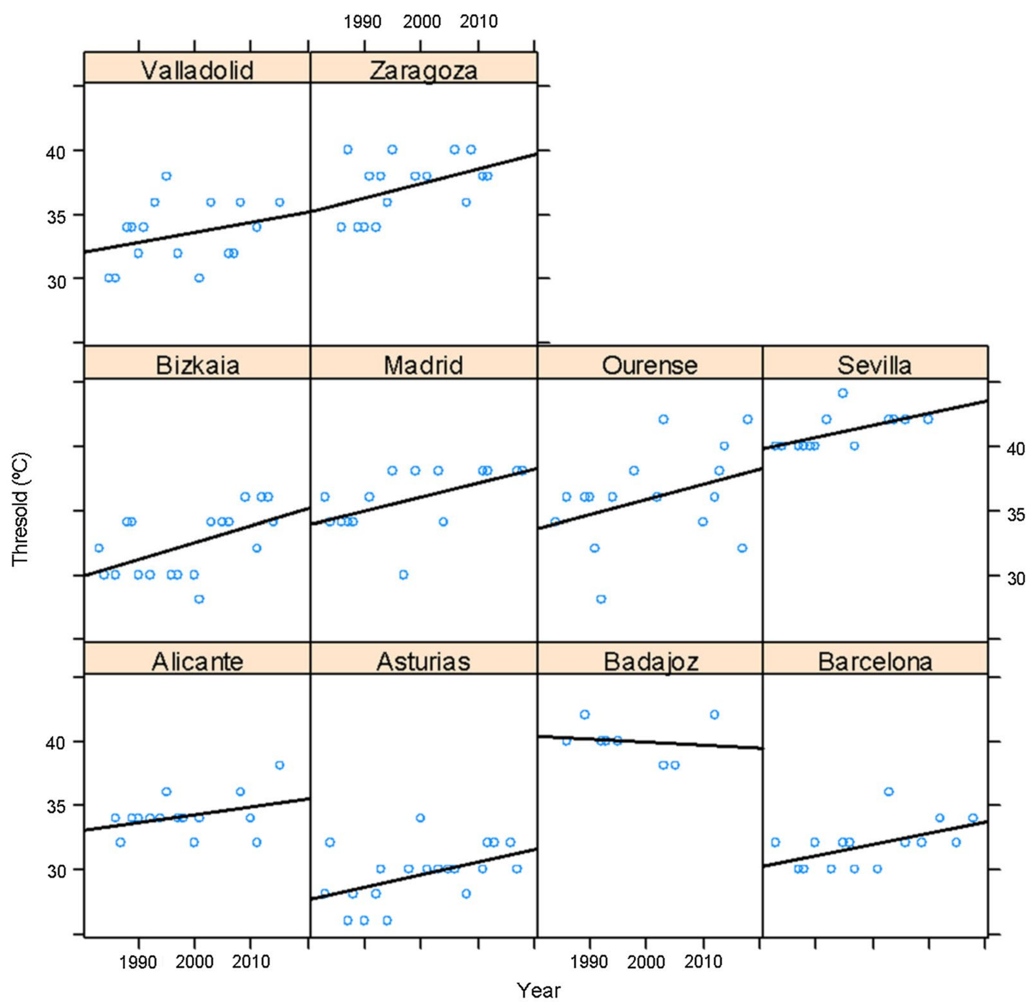

Fig. 3 Linear fit based on the threshold temperature in the years of the study period in each of the regions considered

Table 1 Average values of daily mortality, daily maximum temperature (Tmax) of the summer months; rate of change in minimum mortality temperatures (MMT) and threshold temperatures (Tthreshold) by region during the 1983–2018 period

Region (capital of region)	Mortality rate 1983–2018	Tmax (℃) summer 1983–2018	MMT trend (°C/decade)	Tthreshold trend (℃/decade)	Pearson correlation
Alicante	2.09	29.6	0.69**	0.51	0.629*
Asturias (Oviedo)	2.89	22.4	0.33	1.01*	0.018
Barcelona	2.14	27.1	0.45*	0.87**	0.628**
Badajoz	2.49	33.0	0.65*	−0.25	−0.142
Bizkaia (Bilbao)	2.23	25.0	0.20	1.32*	0.342
Madrid	1.76	29.9	0.60*	1.08**	0.406
Orense	3.22	29.3	0.66*	1.05	−0.330
Sevilla	2.06	34.1	1.14**	0.93**	0.419
Valladolid	2.09	27.0	−0.80	0.98	−0.476
Zaragoza	2.50	30.5	0.62*	1.29*	0.573*

Pearson correlation coefficients of the bivariate correlations obtained from the series of annual values of Tthreshold and MMT. *Significance $p < 0.05$; ** Significance $p < 0.01$

regions (Badajoz, Orense and Valladolid) the correlations have a negative sign.

The CCF calculated between the series of MMT and Tthreshold values did not show statistically significant lags, except in Barcelona, Alicante and Zaragoza, in which case the significant associations were established in lag zero, as shown in Fig. 4.

On the other hand, Table 2 shows the results obtained in the linear mixed model, where for all of the regions analyzed, there was a statistically significant, increasing trend in Tthreshold values.

Table 3 shows the rate of increase in Tmax in the summer months in each of the regions analyzed during the 1983–2018 period and the future rate of increase in Tmax values foreseen for the 2051–2100 time horizon under an RCP8.5 emissions scenario.

Discussion

The primary result of this study is that, at the global level, Tthreshold has increased in Spain over the 36-year period of analysis (1983–2018), which indicates a gradual process of population adaptation to heat waves. These results agree with those of studies of relative attributable risks that analyze the impact of heat waves in Spain [9] and with the results obtained from studies in other locations both in Europe and in the United States [2, 3, 27, 28].

The rate of evolution of Tthreshold observed here is around 0.57 °C/decade and is similar to the rate of evolution of MMT for all of Spain, established at 0.64 °C/decade [16]. Despite this, the rate of increase in Tthreshold is greater than that of MMT in 8 of the 10 considered regions, which indicates that the population adapts more rapidly to the more extreme values of Tthreshold than to the lower temperature values that correspond to MMT. This could be related to the measures put into place specifically related to heat waves (prevention plans to address high temperatures, air conditioning, health alerts) [31].

Similar to the evolution of MMT [16], there are great geographic differences in the evolution of Tthreshold values. Table 1 shows a contrast between the rate of increase of up to 1.32 °C/decade, such as occurs in Bizkaia, and other regions which may even show a decline, such as in the case of Badajoz (−0.25 °C/decade). There are diverse factors, as the mean age of the population per each region, that could help to explain these variations between regions with different climatic and demographic contexts, some of which could potentially be influenced, such as health spending [20] or the level of income [22]. Others, such as demographic structure [25] or the rural/urban character, also influence the different impacts of heat [23], but would be difficult to modify.

However, there are other factors that operate at a sub-regional level that are probably important in explaining the different behavior of heat with respect to mortality; for example, the age of built structures [21], their quality and insulation [24] and even the access to air conditioning [14]. The existence of *green roofs and walls* [5] and the accessibility of green zones could also influence mortality due to heat [26] and, therefore, could change the relationship between temperature and mortality. Explanations of the differences in the evolution of MMT should also take place at the sub-provincial level considered here.

The average maximum temperatures in the summer months in Spain have increased at a rate of 0.41 °C/

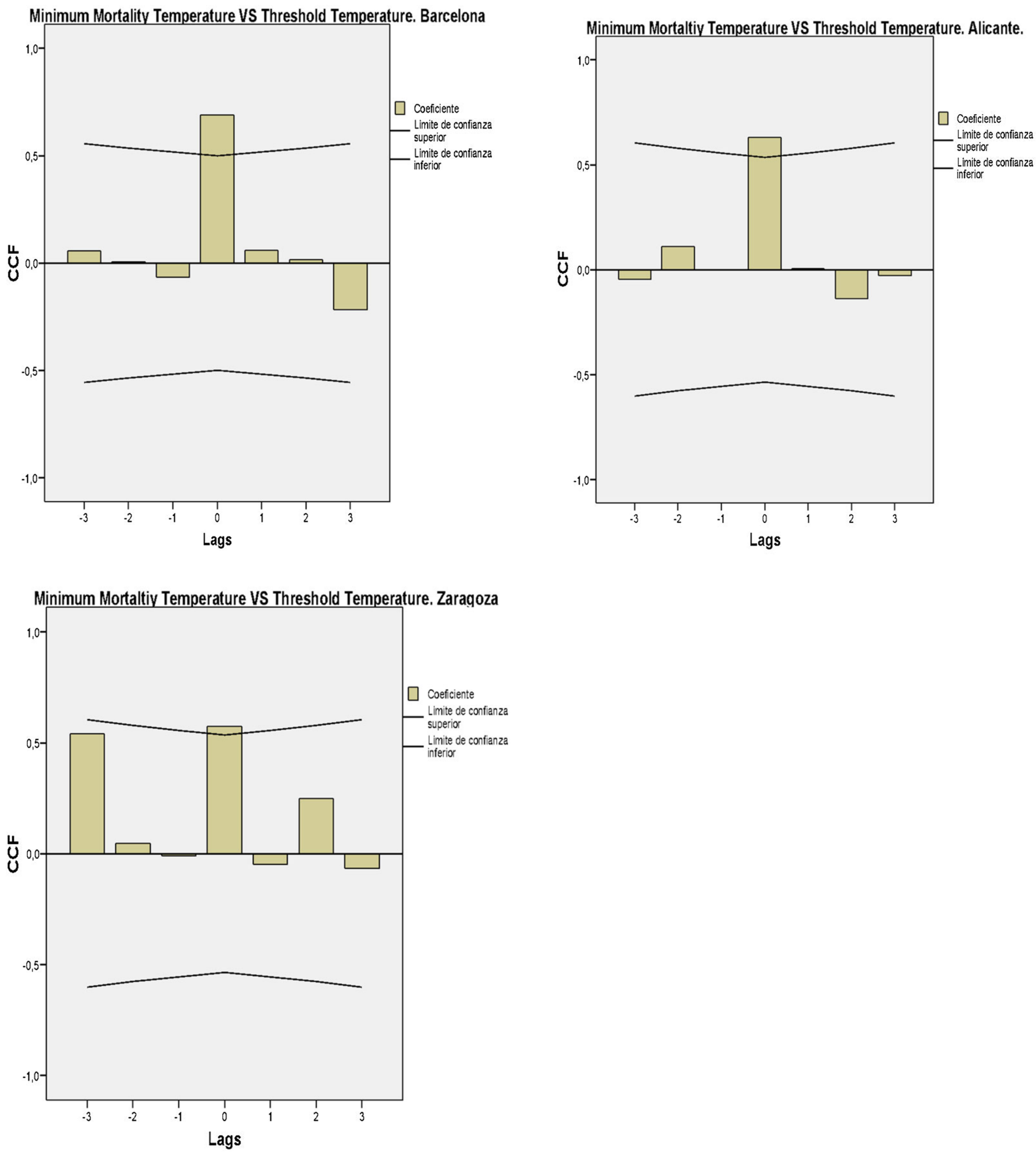

Fig. 4 Cross-correlation functions (CCF) between the annual series of minimum mortality temperatures (MMT) and the threshold temperatures (Tthreshold) for the 1983–2018 period for the regions of Barcelona, Alicante and Zaragoza, respectively

decade [16]. Therefore, at the global level it can be said that a process of adaptation to heat waves exists in Spain, in accordance with the hypothesis that adaptation to heat waves exists when the rate of increase in Tthreshold is greater than the rate of growth in Tmax [10, 17]. However, the regional differences mean that this is not the case for the regions as a whole. Table 3 shows a comparison of the rate of increase in

Table 2 Results of the mixed model to determine the annual increase (d$year) in Tthreshold for all of the regions considered

	Estimate	Std.err	Wald	Pr(>|W|)
Intercept	−80.1230	54.5602	2.16	0.142
d$year	0.0574	0.0271	4.49	0.034*

Region was used as a factor of random effects

* Significance $p < 0.05$

Table 3 Rate of evolution of maximum daily temperature (Tmax) in the summer months for the 1983–2018 period and for future Tmax foreseen for the 2051–2100 time horizon under an RCP8.5 emissions scenario

Region	Tmax 1983–2018 trend (°C/decade)	Tmax 2051–2100 trend (°C/decade)
Alicante	0.19	0.62
Asturias (Oviedo)	0.25	0.46
Barcelona	0.49	0.57
Badajoz	0.42	0.69
Bizkaia (Bilbao)	0.06	0.68
Madrid	0.58	0.72
Orense	0.57	0.65
Sevilla	0.42	0.62
Valladolid	0.20	0.78
Zaragoza	0.57	0.91

Data were taken from Follos et al. [16] and Díaz et al. 2019, respectively

Tthreshold (Table 1) with the increase in Tmax for the summer months during the 1983–2018 period. These findings show that adaptation can be said to be taking place in the regions as a whole, except in Badajoz.

Table 3 also shows the potential future increase in Tmax for the summer months for the 2051–2100 time horizon, considering a high emissions scenario RCP8.5 (Díaz et al. 2019). A similar process to that described here would suggest that if the rate of increase in Tthreshold is sustained, there will be a process of adaptation in the future to temperatures in all regions, with the exception of Alicante and Badajoz.

Despite the fact that there is similar behavior in the evolution of the MMT series and Tthreshold series, they represent different conceptualizations. This highlights that a statistically significant correlation exists between both annual series in only three of the regions analyzed. In the cases in which this association exists, both series are in sync, that is, MMT changes in the same year as does Tthreshold.

One of the limitations of this study is that it considered, at most, a 36-year series. Given that there was only one Tthreshold value per year, only 36 values of Tthreshold were included. This precluded carrying out the sensitivity analyses that are typical of time series methodologies, such as Jack-Knife [13]. The use of a relatively short data series (36 years, 36 values) could provide uncertainty in the determinations of the slopes of the linear fits. This uncertainty is inherent in this type of estimations with such scarce number of data. In addition, in some of the regions considered, there were years without a heat wave, therefore it was not possible to determine a Tthreshold value, which also removed data from the series of Tthreshold values.

A representative observatory was used as a reference for an entire region, which could give rise to bias in the assignment of exposure temperatures of the population [7]. The possible bias due to not controlling for air pollution variables was minimized through the use of prewhitened series of mortality rates and through directly relating mortality anomalies with temperature anomalies to determine Tthreshold values.

Conclusions

The temporal evolution of the series of both, MMT and Tthreshold temperatures, can be used as indicators of the population adaptation to heat. The temporal evolution of Tthreshold has important geographic variation, probably related to sociodemographic and economic factors that should be studied at the local level. It is important to keep in mind that the activation of heat prevention plans should take place based on these heat wave definition threshold temperatures, and should be implemented at the local level [34]. An analysis of the temporal evolution of Tthreshold is key not only in updating these threshold levels periodically, as suggested by the WHO [34], but also as an indicator of the population adaptation to heat. Knowing which variables influence changes in Tthreshold levels and modifying them to favor adaptation processes could be a key tool in adaptation to climate change. If this population adaptation to heat is achieved, attributable mortality could be dramatically reduced [18, 30] (Díaz et al. 2019).

Abbreviations

MMT: Minimum mortality temperature; Tthreshold: Threshold temperature; Tmax: Maximum daily temperature; ICD: International Classification of Diseases; CCF: Cross-correlation functions.

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Disclaimer

This paper reports independent results and research. The views expressed are those of the authors and not necessarily those of the Carlos III Institute of Health (Instituto de Salud Carlos III).

Authors' contributions
LJA: providing and analysis of data; elaboration and revision of the manuscript. DJ: original idea of the study. Study design: elaboration and revision of the manuscript. FF: providing and analysis of data; elaboration and revision of the manuscript. VJM: providing and analysis of data; elaboration and revision of the manuscript. NMÁ: providing and analysis of data; elaboration and revision of the manuscript. CD: providing and analysis of data; elaboration and revision of the manuscript. LMY: providing and analysis of data; elaboration and revision of the manuscript. SMG: epidemiological study design. Elaboration and revision of the manuscript. LC: original idea of the study. Study design; elaboration and revision of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials
It is an ecological analysis so the study does not involve human subjects.

Declarations

Ethics approval and consent to participate
This study works with aggregate data, therefore there are no individual data. Therefore, the consent to participate is not applicable.

Consent for publication
This study works with aggregate data, therefore there are no individual data. Therefore, the consent to publish is not applicable.

Competing interests
The researchers declare that they have no conflicts of interest that would compromise the independence of this research work. The views expressed by the authors do not necessarily coincide with those of the institutions whose affiliation is indicated at the beginning of this article.

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