Science of the Total Environment 890 (2023) 164412

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impact of urban heat islands on morbidity and mortality in heat waves: Observational time series analysis of Spain's five cities

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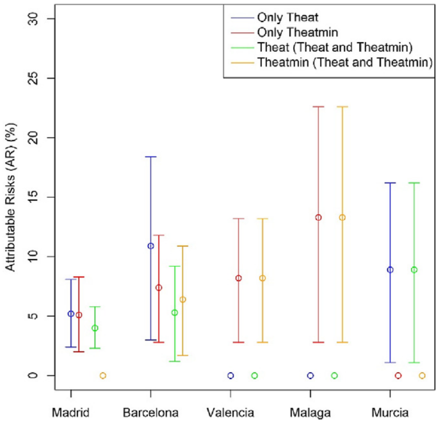
HIGHLIGHTS

- The UHI effect was observed in Tmin but not in Tmax.
- The UHI value ranged from 1.2 °C in Murcia to 4.1 °C in Valencia.
- The association in inland cities on morbidity and mortality is with Tmax.
- The association in coastal cities on morbidity and mortality is with Tmin.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Pavlos Kassomenos

Keywords:
Morbidity
Mortality
Heat wave
Urban heat island
Maximum daily temperature
Minimum daily temperature

ABSTRACT

Urban heat islands (UHIs) have become an especially relevant phenomenon as a consequence of global warming and the growing proportion of people living in cities. The health impacts that are sometimes attributed to the rise in temperature generated in an UHI are not always adequately justified.

The objective is to analyse what effect UHIs have on maximum (Tmax) and minimum daily temperatures (Tmin) recorded in urban and non-urban observatories, and quantify the impact on morbidity and mortality during heat waves in Spain's five cities.

Data were collected on natural-cause daily mortality and unscheduled emergency hospital admissions (ICD-10: A00-R99) registered in these 5 cities across the period 2014–2018. We analysed daily Tmax and Tmin values at urban and non-urban observatories in these cities, and quantified the impact of Tmax and Tmin values during heat waves in each of these cities, using GLM models that included Tmax only, Tmin only, and both. We controlled for air pollution and other meteorological variables, as well as for seasonalities, trend and the autoregressive nature of the series.

The UHI effect was observed in Tmin but not in Tmax, and proved to be greater in coastal cities than in inland and more densely populated cities. The UHI value in relation to the mean Tmin in the summer months ranged from 1.2 °C in Murcia to 4.1 °C in Valencia (difference between urban/non-urban observatories). The modelling process showed that, while a statistically significant association ($p < 0.05$) was observed in inland cities with Tmax for mortality and hospital admissions in heat waves, in coastal cities the association was obtained with Tmin, and the only impact in this case was the UHI effect on morbidity and mortality.

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http://dx.doi.org/10.1016/j.scitotenv.2023.164412
Received 27 March 2023; Received in revised form 10 May 2023; Accepted 21 May 2023

No generalisations can be made about the impact of UHI on morbidity and mortality among the exposed population in cities. Studies on a local scale are called for, since it is local factors that determine whether the UHI effect will have a greater or lesser impact on health during heat-wave events.

1. Introduction

Rising population concentrations in cities are one of the major challenges of the 21st century. The increase in people with greater exposure to risks deriving from climate change, has contributed to the steady migration to urban areas. According to the data portal of the Global Migration Data Analysis Centre (UN International Organisation for Migration), the global population not born in the cities where they live, is on the rise, going from an initial 30 % in 1950 to 55 % in 2018, and is estimated to reach 60 % by 2030 (IOM, 2022; IPCC, 2022). It is envisaged that overall, up to 2.5 billion more people around the world are likely to be living in these habitats by 2050.

This higher concentration of people in urban areas, together with increased urbanisation, the quality of urban design and the building materials used, anthropogenic activity, the shrinking of natural areas, as well as other geographical and meteorological factors, have given rise to the phenomenon known as “urban heat island” (UHI) (EPA, 2022b; Maxwell et al., 2018).

The UHI is a phenomenon well described in the literature (Arnfield, 2003; Barrao et al., 2022; Oke, 1973, 1982). It is characterised by a rise in temperatures in urban centres as compared to outlying rural areas and even nearby suburbs. This alteration affects minimum temperatures in particular, which in some cases can display differences of several degrees with respect to surrounding rural areas (Arnfield, 2003; EPA, 2022b).

UHIs have important repercussions on population health and wellbeing (WHO Regional Office for Europe, 2021). Many studies have ascertained their effect on mortality and morbidity around the world (Cheng et al., 2019; Díaz et al., 2006; Ho et al., 2023). It has even been observed that there are relevant differences in these health indicators depending on the meteorological nature of the heat wave itself and its combination with certain air pollutants (Ruiz-Páez et al., 2023).

It is clear that, when drawing up plans to combat climate change and the effects of heat, it is essential to assess the related risks and impacts, create a strategic framework, and devise specific actions, so as to build up resilience and mitigate vulnerability. These risks and impacts must be addressed at a local level (WHO Regional Office for Europe, 2021) because for adaptation to be successful, knowledge, competence and local capabilities are required, something that can only be tackled by multi-actor alliances between individuals, households and the community, as well as governments and local entities with decision-making capacity, and other organisations with knowledge and intervention capabilities (Díaz et al., 2015; Dodman, 2012).

The UHI effect occurs at all times of the year, including winter (Macintyre et al., 2021). The UHI is mainly related to the structure of cities and to their geographical and meteorological characteristics (Maxwell et al., 2018), regardless of the occurrence or not of heat waves. It is in the summer months, and especially when temperatures are extremely high, i.e. in heat waves, that the analysis of their possible impact on health is most relevant. This urban warming poses a threat, especially in cities where extreme thermal events, such as heat waves, not only occur but are being magnified and intensified by the effects of climate change (EPA, 2022a; Santamouris, 2014).

When it comes to addressing the problem of the impact of heat-wave temperatures, different studies indicate that, while it is maximum daily temperatures that best correlate with heat-wave-related mortality (Alberdi et al., 1998; Díaz et al., 2002; Díaz et al., 2015; Guo et al., 2017), it is minimum temperatures that best account for hospital admissions (Linares and Díaz, 2008; Royé, 2017).

In addition to the mere meteorological correlation between maximum and minimum temperatures, from a health point of view, there is also an association between them. Ambient heat during the night might interrupt the normal physiology of sleep. The subsequent health effects of reduced sleep are numerous, such as immune system damage, increased susceptibility to cardiovascular disease, chronic illnesses, systemic inflammation, and psychological and cognitive damage. High ambient temperatures during the night can affect circadian thermoregulation. Some studies suggested that poor sleep was associated with elevated night-time warming. (He et al., 2022). Furthermore, one study suggested a connection between hot nights and mortality in areas in southern Europe (Royé et al., 2021).

Although there have been recent studies analysing the analysis of the UHI effect on daily mortality in different Spanish and European cities, this has been based on satellite temperature estimates (Iungman et al., 2023). However, to date, there are very few studies on this topic based on data obtained from weather station observations (Tan et al., 2010). The aim of our work is to establish the impact of heat wave temperatures on daily mortality and emergency hospital admissions through a comparative analysis of the effect of actually recorded temperatures, both daily maximum and daily minimum. In addition, it would include the joint effect of both variables, controlling simultaneously for other meteorological variables (humidity, wind speed, sunshine, and pressure trend) in order to obtain their impact in each city. The research questions posed are: Which of the two temperatures (maximum or minimum daily) really represents the greatest health impact (measured through the morbidity and mortality of the population)? and How decisive is the impact on UHI morbidity and mortality?. This study therefore sought to analyse this impact on daily mortality and emergency daily hospital admissions registered in Spain's five provincial capitals across the period 2013–2018.

2. Material and methods

Firstly, we selected the most populated cities in Spain at 1 January 2021, according to data supplied by the National Statistics Institute (*Instituto Nacional de Estadística/INE*). To be able to detect the existence of UHIs, these cities were additionally required to have one meteorological reference observatory, as specified by the State Meteorological Agency (*Agencia Estatal de Meteorología/AEMET*), both in and outside their urban centre. The 5 cities that met both conditions were Madrid, Barcelona, Valencia, Malaga and Murcia. Fig. 1 shows the location of the meteorological reference observatories used in this study, both urban and non-urban, for each of the five cities analysed.

2.1. Dependent variables

We analysed daily mortality due to all causes except accidents (ICD-10: A00-R99) registered in each city in the summer months (June–September), across the period 2013–2018. In addition, we also worked with daily emergency hospital admissions due to all causes except accidents (ICD-10: A00-R99) registered at the hospitals in each city analysed. Both data-sets were supplied by the National Statistics Institute.

2.2. Independent variables

To characterise the UHI effect, we obtained the maximum daily temperature (Tmax) and minimum daily temperature (Tmin) values in degrees Celsius (°C) recorded by both urban and non-urban observatories (Fig. 1) across the study period.

In the process of modelling and analysing the impact of Tmax and Tmin during heat waves on mortality and emergency hospital admissions, we solely considered the observatory located in the city interior, since it is

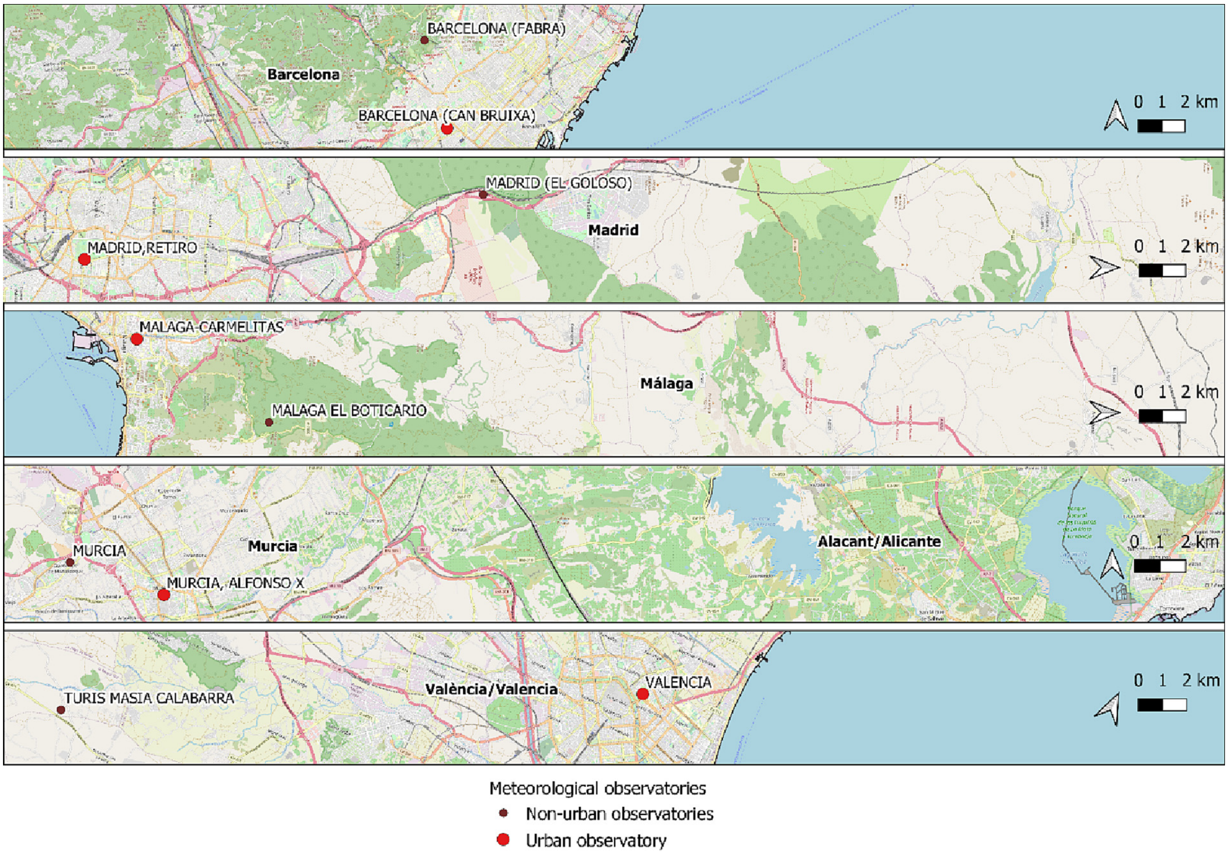

Fig. 1. Location of urban and non-urban reference observatories in each of the 5 cities analysed.

this that best represents citizens' exposure to the different meteorological variables. In addition, these observatories also register mean daily relative humidity (%), mean daily wind speed (km/h), daily sunlight (hours), and mean daily air pressure (hPa).

2.3. Variables derived from the independent variables

With the aim of calculating the impact that Tmax and Tmin have on daily mortality in heat waves, the value of the heat-wave definition threshold temperature (Tthreshold) was taken into account for both Tmax and Tmin. These Tthresholds are calculated in accordance with epidemiological temperature-mortality studies previously undertaken for each province, and are used by the Spanish Ministry of Health for activation of Heat Wave Prevention Plans (Ministerio de Sanidad, 2022). The Tthreshold values calculated for both Tmax (Tthresholdmax) and Tmin (Tthresholdmin) are shown in Table 1.

Based on these Tthresholds, we then calculated the variables that take heat-wave temperatures into account, defined as follows:

$$\mathit{Theat} = 0;\ \text{if Tmax} < \text{Tthresholdmax}$$

$$\mathit{Theat} = \text{Tmax} - \text{Tthresholdmax};\ \text{if Tmax} > \text{Tthresholdmax}$$

$$\mathit{Theatmin} = 0;\ \text{if Tmin} < \text{Tthresholdmin}$$

$$\mathit{Theatmin} = \text{Tmin–Tthresholdmin};\ \text{if Tmin} > \text{Tthresholdmin}.$$

The average intensity of heat waves is obtained by performing the arithmetic mean of the Theat values in heat waves (Theat >0). Similarly for Theatmin.

In view of the relative importance of a heat wave's duration (a heat wave that lasts 2 days will not have the same impact as one that lasts 20 consecutive days) and chronological number in the year (the mortality impact of the first heat wave of the year, in which there are more vulnerable persons (Díaz et al., 2002), is not the same as that of successive heat waves), two new variables were created:

(i) *Durola*, which takes into account the number of days that a heat wave lasts, such that, if the heat wave lasts 2 days, *durola* equals 2, if it lasts 3 days *durola* equals 3, and so on successively; and

(ii) *Numola*, which takes into account the heat wave's chronological number in the year, such that, for the first heat wave, *numola* equals 1, for the second, *numola* equals 2, and so on successively.

Table 1
Values of the heat-wave definition threshold temperatures for maximum daily temperature (Tthresholdmax) and for minimum daily temperature (Tthresholdmin), according to data from the Ministry of Health (Ministerio Sanidad, 2022) and percentiles to which those temperatures correspond in the series of maximum and minimum daily temperatures, respectively, for the summer months (June–September); population density (inhabitants/km^2) and quartiles to which this corresponds in respect of Spain's 52 provincial capitals; coastal city = 1, non-coastal city = 0.

City	Tthresholdmax (°C) Percentile	Tthresholdmin (°C) Percentile	Population density (inhab/km^2) /Quartiles	Coastal
Madrid	34 °C P82	22 °C P92	5332.7 Q1	0
Barcelona	32 °C P96	24 °C P96	15,987.6 Q1	1
Valencia	34 °C P95	24 °C P92	5877.6 Q1	1
Malaga	40 °C P99	26 °C P99	1445.7 Q2	1
Murcia	34 °C P97	23 °C P96	507.1 Q3	0

Given that the variables Theat and Theatmin can have an effect on morbidity and mortality at different time lags, up to 5 lags were introduced for these variables (Díaz et al., 2002; Díaz et al., 2015), creating the variables Theat1, Theat2, etc., and Theatmin1, Theatmin2, etc.

Similarly, to estimate the effect of the existence or non-existence of a UHI effect at a daily level, we created the variable T_{UHI}, defined as follows:

$$T_{UHI} = \text{Tmin\_urban–Tmin\_non} - \text{urban; if Tmin\_urban} > \text{Tmin\_non} - \text{urban}$$

$$T_{UHI} = 0; \text{ if Tmin\_urban} < \text{Tmin\_non} - \text{urban}$$

Hence, positive T_{UHI} values will indicate the existence of a heat island effect.

The heat island intensity is obtained as the arithmetic mean of the T_{UHI} values.

Since each city's urban and non-urban observatories are situated in the same meteorological weather-forecast area, this is a reliable indicator of the overheating experienced by the urban population.

Previous studies show that changes in air pressure can also have an effect on morbidity and mortality (González et al., 2001). To take this effect into account, we created the variable *Pressure trend* (PT), defined as follows:

$$PT = Pt–Pt - 1$$

where Pt is the air pressure on a given day ("today's air pressure") and Pt-1 is the air pressure on the preceding day ("yesterday's air pressure").

For the other meteorological variables considered, as many as 14 time lags were introduced (Gómez González et al., 2023).

Lastly, to take into account which geographical factors can influence T_{UHI} values, we included the city's coastal or non-coastal setting, using a dichotomous variable that is zero if it is non-coastal and 1 if it is coastal. Likewise, population density in inhabitants/km^2 was considered for each city, along with its stratification in quartiles with respect to the 52 Spanish provincial capitals. These values are shown in Table 1.

Also included in the models were the daily mean concentrations (μg/m^3) of PM_{10}, NO_2 and O_3, sourced from the mean readings taken by the measuring stations belonging to the Ministry for Ecological Transition and Demographic Challenge (*Ministerio para la Transición Ecológica y Reto Demográfico/MITERD*) in the cities analysed.

2.4. Other control variables

To be able to control for the possible effect which similar seasonalities, trend and autoregressive nature among the dependent and independent variables might have on the modelling process, we introduced the variables *sin365, cosin365, sin180, cosin180, sin120, cosin120, sin90, cosin90* to take into account annual, six-monthly, four-monthly and three-monthly seasonalities respectively, using the sine and cosine functions.

We also controlled for days of the week and Public Holidays across the study period.

Trend was controlled for using the variable n1: n1 is a counter that equals 1 on the first day of the series, 2 on the second day, and so on successively.

Possible overdispersion was controlled for by introducing the first-order autoregressive of the dependent variable.

2.5. UHI characterisation process and calculation of attributable mortality

A double-modelling strategy was implemented. On the one hand, to take into account the influence of local factors such as population density or coastal setting on daily T_{UHI} values, a mixed linear model (link = identity) was fitted, using T_{UHI} as the dependent variable, and the coastal setting of the city analysed and the quartile to which it belonged by virtue of its population density, as independent variables. On the other hand, to quantify the impact of Theat and Theatmin for both daily mortality and emergency hospital admissions, generalised linear models (GLMs) were fitted with the Poisson link. In this way, along with all the lagged meteorological and control variables, we fitted one model by introducing the variables linked to Theat, a second model by introducing the variables linked to Theatmin, and lastly, a third model by introducing Theat and Theatmin jointly.

We used the backward-stepwise procedure to select variables that proved significant at $p < 0.05$. Based on the coefficients of the estimators of these statistically significant variables, we then quantified the relative risks (RRs) for every one-unit increase in the independent variables, and based on these, their attributable risks (ARs) in so much per cent, using the equation: AR = 100*(RR-1) /RR.

Mortality and attributable hospital admissions were calculated on the basis of the AR values for Theat and Theatmin, as well as the values of daily mortality or hospital admissions at the significant lags established in the GLM models (Carmona et al., 2016).

Data-cleaning was performed in R. The mixed models were fitted using the IBM SPSS V29 computer software platform, and all other statistical analyses were performed using the STATA v15 computer software package (StataCorp LP, College Station, Texas 77,845 USA).

3. Results

The descriptive statistics of the dependent and independent variables used in this study are listed in Table 2.

Table 2
Descriptive statistics of the dependent variables. In the case of the meteorological variables, the data correspond to the urban observatory (situated in an urban centre). Summer months (June–September 2013–2018). *N* = 732.

	Madrid	Barcelona	Valencia	Malaga	Murcia
Daily mortality					
Mean	60.6	24.3	14.6	8.4	6.4
Maximum	95	39	32	20	15
Minimum	31	12	4	1	1
SD	10.1	5.2	4.0	3.0	2.5
Daily hospital admissions					
Mean	475.8	289.1	215.4	104	113.4
Maximum	647	396	342	151	165
Minimum	222	170	115	63	37
SD	85.4	47.7	38.9	16.8	18.8
Maximum daily temperature (°C)					
Mean	31.2	27.8	28.9	30.4	28.4
Maximum	40.0	37.0	41.6	41.7	39.4
Minimum	18.2	18.1	20.8	23	21
SD	4.6	2.5	2.6	3.2	2.4
Minimum daily temperature (°C)					
Mean	18.5	20.6	21.2	20.8	21.0
Maximum	28.9	27.3	27.0	28.3	27.5
Minimum	9.6	12.0	24.0	12.9	11.4
SD	3.4	2.3	2.4	2.5	2.2
Daily relative humidity (%)					
Mean	45.3	69.3	64.0	58.3	ND
Maximum	84.7	94.5	90.5	85.1	ND
Minimum	26.2	30.8	25.0	25.1	ND
SD	9.8	8.3	10.3	15.3	ND
Daily wind speed (km/h)					
Mean	6.7	14.0	10.8	12.4	ND
Maximum	13.3	32.9	29.0	37.9	ND
Minimum	2.4	0.0	4.4	4.7	ND
SD	1.9	3.1	2.8	3.8	ND
Daily pressure (hPa)					
Mean	940.0	1013.3	1008.0	1002.0	ND
Maximum	950.6	1029.0	1021.0	1023.5	ND
Minimum	929.2	953.3	954.8	955.2	ND
SD	2.9	35.3	16.5	38.2	ND
Daily sunlight (hours)					
Mean	11.2	8.3	9.1	10.6	10.5
Maximum	14.4	12.7	12.0	13.7	14.0
Minimum	0.3	0.0	0.0	0.0	0
SD	2.9	3.2	2.8	2.8	2.7

ND = No Data.

Table 3
Number of heat waves and mean intensity of these heat waves (°C); correlation coefficients between maximum daily and minimum daily temperature; difference between the means for the summer months (°C) of minimum and maximum daily temperatures, between the urban and non-urban observatories in each city.

	No. heat waves/ mean intensity (°C)	Correlation coefficient Tmax vs. Tmin	Difference Tmin Urban – Non-urban (T_{UHI})	Difference Tmax Urban – Non-urban
Madrid				
Theat	232 /2 °C	0.948**	1.3 °C	0 °C
Theatmin	109/1.3 °C			
Barcelona				
Theat	25 /1.2 °C	0.799**	3.2 °C	−0.1 °C
Theatmin	66/0.8 °C			
Valencia				
Theat	20/2.0	0.609**	4.1 °C	−1.6 °C
Theatmin	71/0.8			
Malaga				
Theat	4/0.9	0.573**	1.9 °C	1.5 °C
Theatmin	18/1			
Murcia				
Theat	11/1.8	0.447**	1.2 °C	0 °C
Theatmin	176/1.4			

** $p < 0.001$.

Table 3 shows the number of heat waves that occurred across the study period at the urban observatory (urban centre) using the heat-wave definition temperature (Tthreshold), based both on the maximum daily temperature (Theat) and minimum daily temperature (Theatmin); also shown is the mean intensity of heat waves (°C), with "mean intensity" being construed as the excess degrees registered on average by each heat wave across the period analysed.

As can be seen, the number of heat waves is higher, if one uses the definition based on the minimum threshold temperature (Theatmin) rather than the maximum threshold temperature (Theat), with the exception of the city of Madrid. That said however, the intensity of the heat waves registered is higher when using the definition based on the maximum as opposed to the minimum threshold temperature, with the exception of the city of Malaga, where these are practically the same.

It is evident that there is a high correlation between maximum daily temperature (Tmax) and minimum daily temperature (Tmin), as can be seen in Table 3, which shows that these correlation coefficients are significant at $p < 0.001$.

The graphs in Fig. 2 show the temperature time trend at the urban and non-urban observatories in each city.

Table 3 also shows the difference between Tmin registered at the urban and non-urban observatories of each city, previously defined as T_{UHI}. As can be seen, the minimum daily temperature values at the urban observatories are higher than those at the non-urban observatories, i.e., the UHI phenomenon is thus apparent in the 5 cities analysed.

This excess can amount to as much as 4.1 °C in the city of Valencia in relation to the values for the whole period, and is higher in coastal cities (Valencia, Malaga and Barcelona) than in non-coastal cities (Madrid and Murcia). This effect is not seen in the maximum daily temperatures registered, with the single exception of Malaga.

Analysis of the daily T_{UHI} values shown in Table 4 indicates that this UHI effect can be as much as 11.2 °C, as in the case of Valencia, and is seen on most days, reaching a figure of 99.6 % of days in the city of Barcelona.

The results of the mixed models indicate that a city's coastal or non-coastal setting is statistically significant at $p < 0.005$ when it comes to accounting for T_{UHI} values. The coastal setting of a city would account for up to 2.2 °C (95%CI: 2.1, 2.4) of the T_{UHI} values. Along with coastal setting, population density also proved to be statistically significant in this mixed model, such that the most densely populated cities, those ranked in Q1, would have T_{UHI} values 1.6 °C (95%CI: 1.4, 1.7) higher than those in Q2, with this value being significant at $p < 0.005$.

Fig. 3a and b show the AR values calculated on the basis of the RR values obtained in the GLM modelling process for both daily mortality and emergency hospital admissions, for the models with Theat only, Theatmin only, and both temperatures as heat-wave indicators. It will be seen in these figures that the highest ARs are found in cities in which the Theat and Theatmin values correspond to the threshold temperatures associated with the highest percentiles.

Table 5 shows the deaths and annual emergency hospital admissions attributable to Theat and Theatmin, along with their 95%CIs, as well as the percentage that these represent in the total number of deaths occurring in these cities in the summer months across the study period.

These values are calculated on the basis of the AR values obtained with the results of the GLM models: firstly, if the variable "Theat only" is included; secondly, if "Theatmin only" is included; and thirdly, when both variables are included.

In the case of the joint model and daily mortality, in which both Theat and Theatmin are included, Theat is the only variable that shows an association in the cities of Madrid and Murcia. In Barcelona, both Theat and Theatmin show an association. In the case of Valencia and Malaga, it is the heat-wave definition based on the minimum daily temperature that would be associated with daily mortality. In the case of hospital admissions, it is only in Madrid that Theat would be associated with daily heat-wave-related hospital admissions, whereas in Barcelona and Valencia it would be Theatmin, and there would be no association in either Malaga or Murcia.

From a quantitative standpoint, the greatest impact on heat-wave mortality is observed in Madrid, where the maximum daily temperatures in heat waves would account for 3.6 % of deaths that occur in the summer months; and if the indicator were minimum daily temperature, then 1.2 % of these deaths would be associated with heat waves.

In the remaining cities, the percentage of attributable mortality accounted for by heat waves, regardless of whether the indicator is maximum or minimum daily temperature, would not exceed 0.7 %. In the case of daily hospital admissions, the percentage of cases accounted for is lower than that of mortality, with the maximum percentage being registered for the city of Madrid, with 0.7 %.

The variable, heat-wave number (*numola*), is shown in the GLM models as being significant with a negative sign, whereas the variable pertaining to heat-wave duration (*durola*) has a positive sign.

4. Discussion

4.1. UHI effect

As can be seen in Table 3, the results obtained in this study for the cities analysed go to show that the UHI phenomenon is almost exclusively observed in minimum daily temperatures, i.e., those recorded early in the morning, which is in line with findings reported by a number of studies on the topic (Arnfield, 2003; EPA, 2022b), though there are other studies that also observe this phenomenon in maximum daily temperatures, albeit to a lesser extent (EPA, 2008). In fact, the effect on night-time values is usually as much as three times higher than the effect on daytime values (Iungman et al., 2023; Chun and Guhathakurta, 2015).

UHI intensity is influenced by a range of factors, e.g., the fact that in these non-urban settings there are areas with vegetation (Hibbard et al., 2017) or, on the contrary, that there are shopping malls with large car parks, or that these are industrial zones (Middel et al., 2021; Voogt, 2000).

When selecting the non-urban meteorological observatories in this study, it was intended that they should have similar conditions in terms of distance to the city centre and similar characteristics of vegetation cover. However, in some cases, there was only one non-urban weather observatory that recorded a time series of meteorological variables without data gaps. The lack of homogeneity of the non-urban observatories is a limitation of the study.

From a quantitative standpoint, the UHI intensity observed in this study with respect to the mean levels shown in Table 3, ranges from values of 1.2 °C to 4.1 °C in the minimum daily temperatures. These values are of the same order of magnitude as those reported by other papers, which can be as much as 12 °C (Heaviside et al., 2017; Memon et al., 2008). A study conducted in Europe, in which some Spanish cities are analysed, quantifies the effect of the UHI at 1.5 °C (range 0.5 °C to 3.0 °C) (Iungman et al., 2023). Specifically, for the cities of Malaga and Barcelona, this effect is estimated at 1.9 °C and 1.09 °C respectively, though, in that study the UHI was established on the basis of mean daily temperature values and not on Tmin values as in our case.

Studies conducted in Madrid (Sánchez-Guevara Sánchez et al., 2017; López-Gómez, 1993) report this effect as being as high as 8 °C, a value close to the 7.1 °C shown in Table 4 for this city. In the case of Valencia, studies undertaken there establish this mean UHI value at 2.3 °C (Lehoczky et al., 2017), a value lower than that of 4.1 °C detected by us for this city, though our data were recorded at meteorological reference observatories, whereas the study cited also contains estimates based on remote sensors (MODIS).

The different UHI intensity shown in Tables 3 and 4 for the cities analysed may be due, not only to different factors relating to the characteristics of a city's outskirts, as described above, but also to its urban characteristics, such as tree coverage, which could possibly cause the urban temperature to drop (Kalkstein and Sheridan, 2003; Marando et al., 2019), as well as other factors, ranging from population density (Oke, 1995; Lee et al., 2020) to the types of buildings, urban structure, or even the colour of the asphalt or number of air-conditioning units (Harlan et al., 2013; Kownacki et al., 2019).

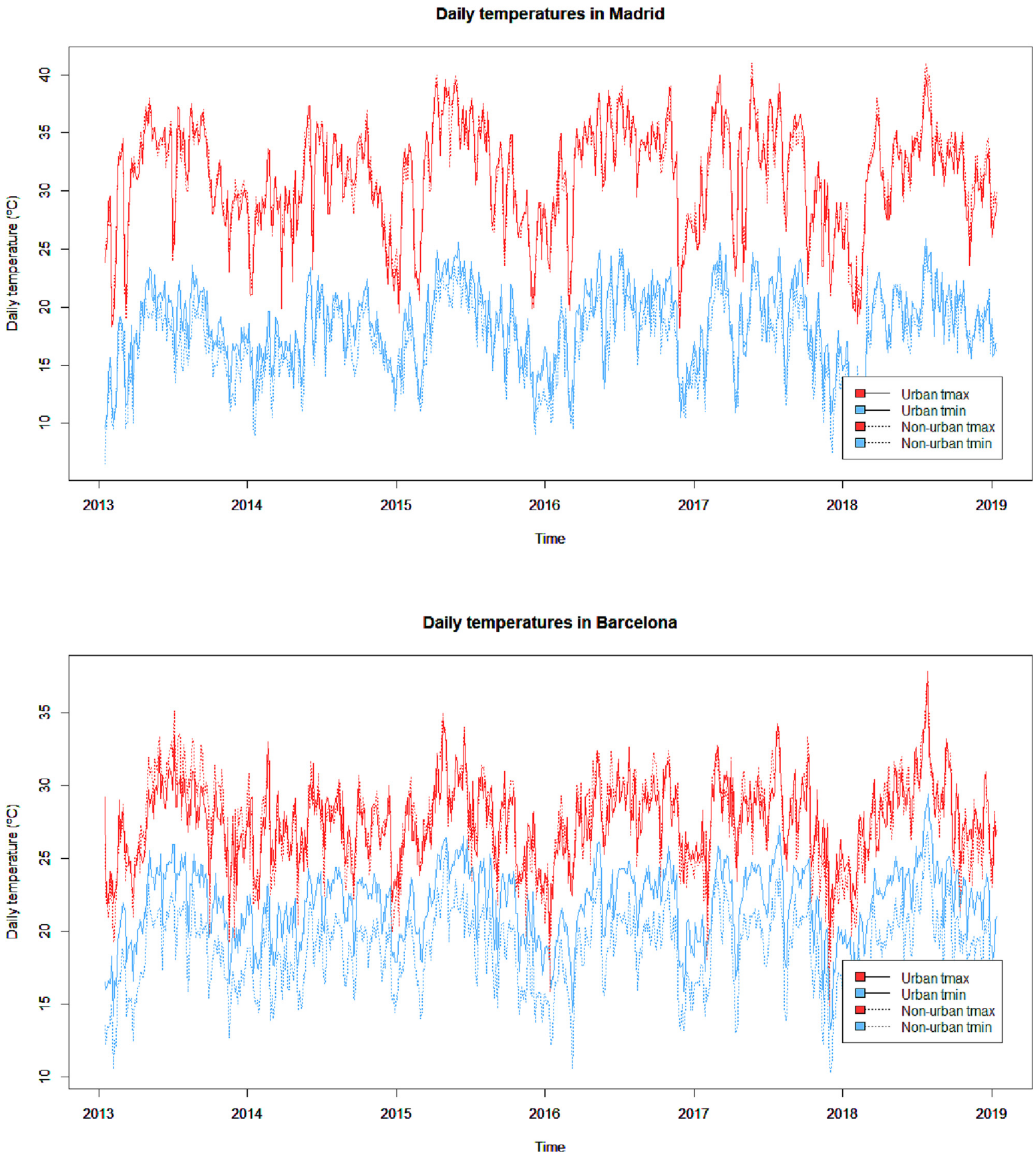

Fig. 2. Time trend in maximum daily temperature (Tmax) and minimum daily temperature (Tmin) at urban and non-urban observatories in each city analysed.

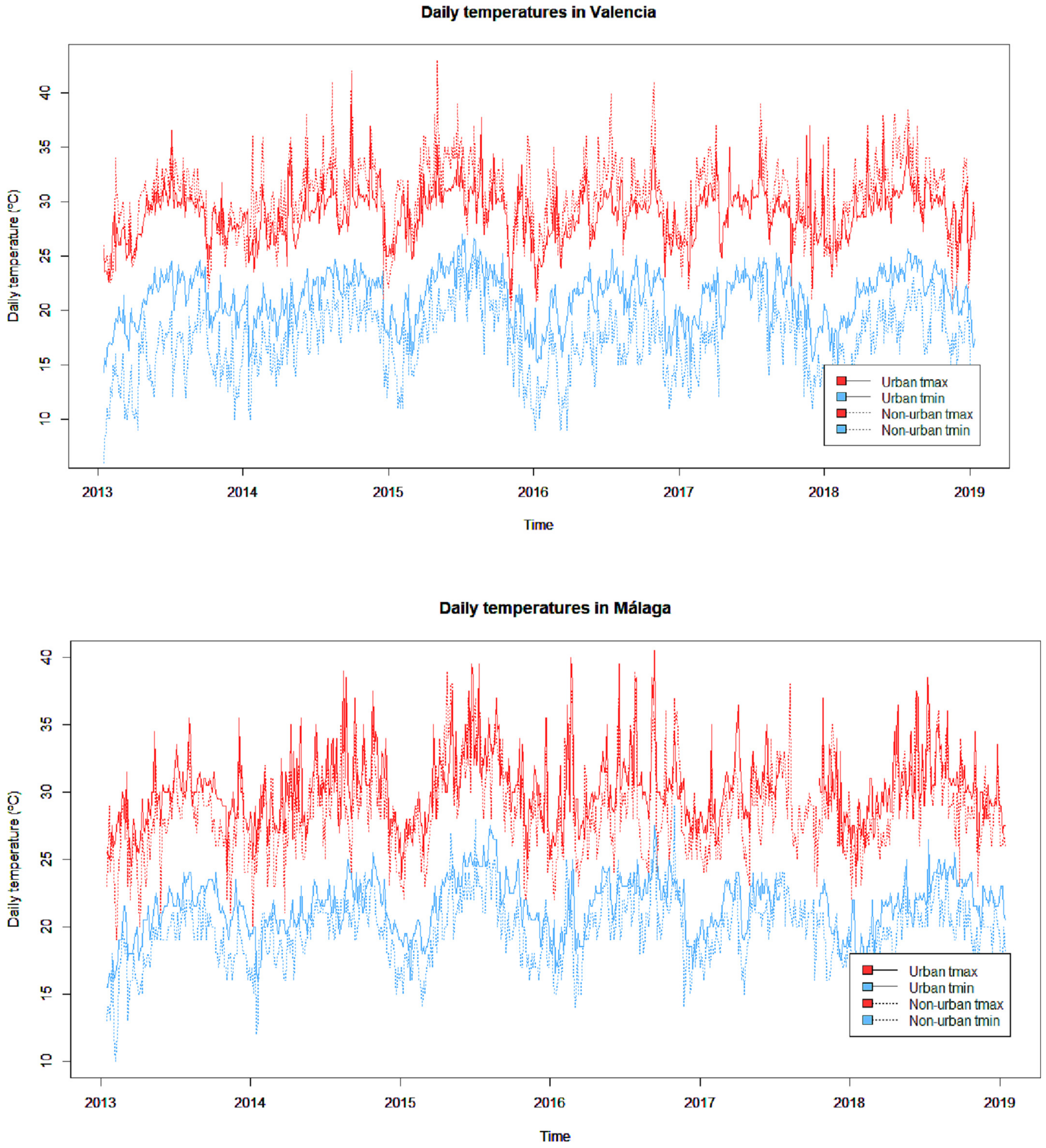

Fig. 2 (*continued*).

The results of the mixed models used for study purposes indicate that population density could account for the different intensity of the UHI effect found in this analysis. Thus, according to Table 2, it is the high population density cities in quartile 1 that would have a greater UHI effect as opposed to those in quartiles 2 and 3. These results are in line with the studies cited above (Oke, 1995; Lee et al., 2020). Judging by our results, it is cities' coastal nature that would exert a greater UHI effect than their population-density factor. In all likelihood, the higher humidity values in coastal areas, as shown in Table 1, act to prevent greater cooling during the night of heat accumulated during the day (Morán, 1944), thereby rendering the UHI effect more pronounced in coastal than in inland cities.

4.2. Tmin vs. Tmax as an indicator of the health effect of heat-wave temperatures

Some scientific studies maintain that it is the maximum daily temperature which shows a better correlation with daily mortality (Díaz et al., 2002; Díaz et al., 2015; Guo et al., 2017), while also including the mean -though not the minimum- daily temperature as a possible indicator (Guo

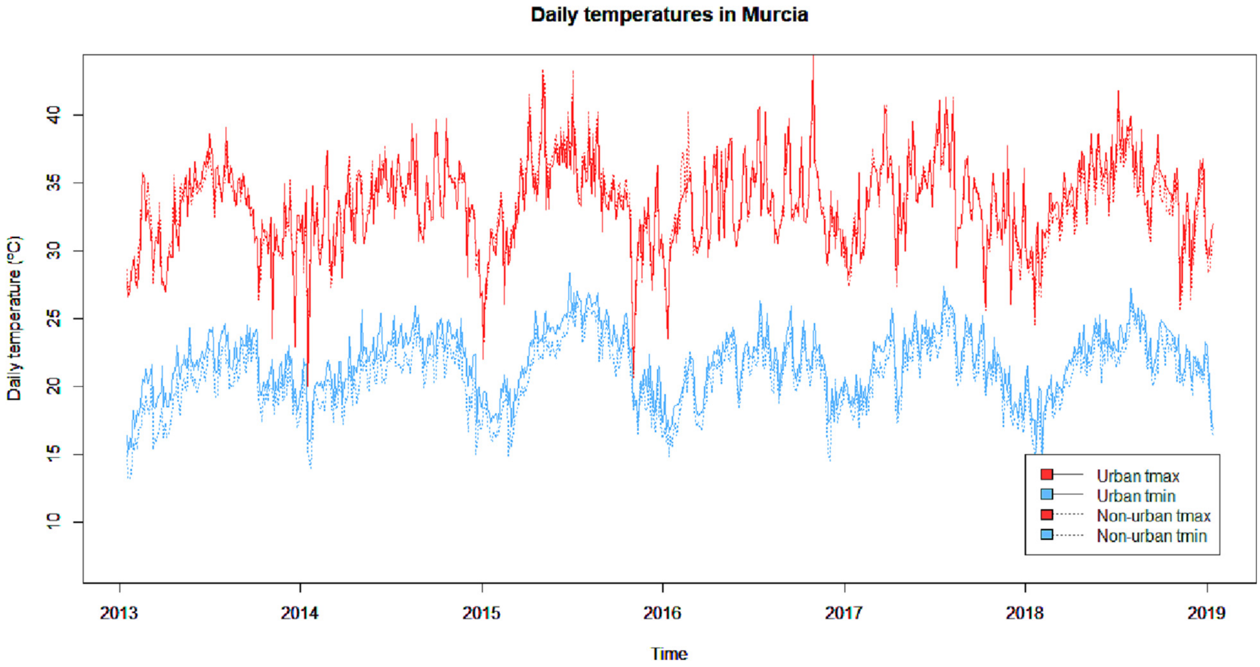

Fig. 2 (*continued*).

et al., 2017). In contrast, other studies suggest that it is high night-time temperatures, i.e., Tmin, which show a greater association with mortality in heat waves during the night, arguing that high nocturnal temperatures increase the risk of developing comorbidities such as diabetes and respiratory and cardiovascular system failures (Kilbourne et al., 1982; Sarofim et al., 2016). The results obtained in our study indicate that one cannot generalise, and that it is local conditions that determine the intensity of the impact of heat waves (WHO Regional Office for Europe, 2021), as well as which temperature indicators are best linked to daily mortality and morbidity respectively. It is evident that the high correlation between Tmax and Tmin observed in Table 3 and Fig. 2 indicates that high Tmax values entail similarly high Tmin values and vice-versa, and one cannot thus identify whether it is Tmax or Tmin that displays a stronger association, unless one were to consider their joint effect in a mathematical model, and determine which of the two explained more variance in the model and had a greater effect on the health indicator used. Hence, the need for a study such as ours.

These are the local characteristics that cause heat-wave definition temperatures and their corresponding percentiles in the temperature series to vary from one place to another (Montero et al., 2010; WHO Regional Office for Europe, 2021), as shown in Table 1.

In turn, it is these percentile values which, in great measure, explain the behaviour, in terms of the number of heat waves and their intensity, shown in Table 3.

During the period analysed in Madrid, a heat-wave definition corresponding to the 82nd percentile indicates that there are heat waves on 18 % of days in the year, as compared to Malaga, where the 99th percentile indicates that there are heat waves on only 1 % of days. Accordingly, there are many more heat waves and more intense heat waves (sum of the difference in degrees over the heat wave threshold temperature) in Madrid than in Malaga. From a health impact point of view, what exerts an influence here is not so much the Tmax or Tmin values reached but rather the size of the gap that separates these temperatures from the heat-wave definition threshold temperature (Díaz et al., 2006).

Table 4
Analysis of the heat island effect of urban heat at a daily level during the summer months —June, July, August, September. T_{UHI} is defined as the difference between the minimum daily temperatures at the urban and non-urban observatories. $T_{UHI} > 0$ indicates the existence of a heat island effect. N = 732.

City	Madrid	Barcelona	Valencia	Malaga	Murcia
T_{UHI} (°C)					
Mean	1.3	3.2	4.1	2.1	1.2
Maximum	7.1	5.9	11.2	9.5	7.4
Minimum	0	0	0	0	0
SD	1.2	0.9	2.2	1.5	0.7
Number of days $T_{UHI} > 0$	581	729	676	591	723
Percentage of days with $T_{UHI} > 0$	79.4	99.6	96.4	84.3	98.8

Moreover, these percentile values are, in turn, those which clearly influence the ARs shown in Fig. 3. As a general rule, threshold temperatures values that correspond to low percentiles in the temperature series of the summer months are associated with low ARs: in contrast, threshold temperature values that correspond to high percentiles are associated with high ARs (Díaz et al., 2015). The AR values calculated in this study in relation to daily mortality, using the models in which Theat only is included, are lower than those obtained in other previous studies (Díaz et al., 2015). This may be due to the different time period analysed, namely, 2000–2009 in the case of Díaz et al.'s, 2015 study versus 2013–2018 in the current study. Different studies in Spain (Díaz et al., 2018) and elsewhere (Åström et al., 2018) have established a clear reduction in the impact of heat on daily mortality, which would account for the decrease in the ARs observed in Madrid and Barcelona, and the fact that no association with mortality is observed in Valencia and Malaga.

From the stance of hospital admissions, it is only in the city of Madrid that maximum daily temperature would have an influence on hospital admissions, a finding in line with other studies which single out Tmin as a better indicator of morbidity than Tmax (Royé, 2017). The maximum daily temperature is the one that is statistically best related to morbidity in the city of Madrid, as shown in Table 5; it is associated with 0.7 % of admissions that occur in heat waves. While the minimum daily temperature only explains 0.3 %, these differences being statistically significant. This result could be attributed to the greater number of heat waves and greater intensity observed in Theat compared to Theatmin in the city of Madrid, according to the results shown in Table 3.

The negative sign accompanying the variable, heat-wave number, in the models, would indicate that it is the first heat wave which has a greater impact on morbidity and mortality, and that this impact wanes in successive heat waves in any given year. This is in line with other studies undertaken in Spain (Díaz et al., 2002) and with the so-called harvesting effect, which

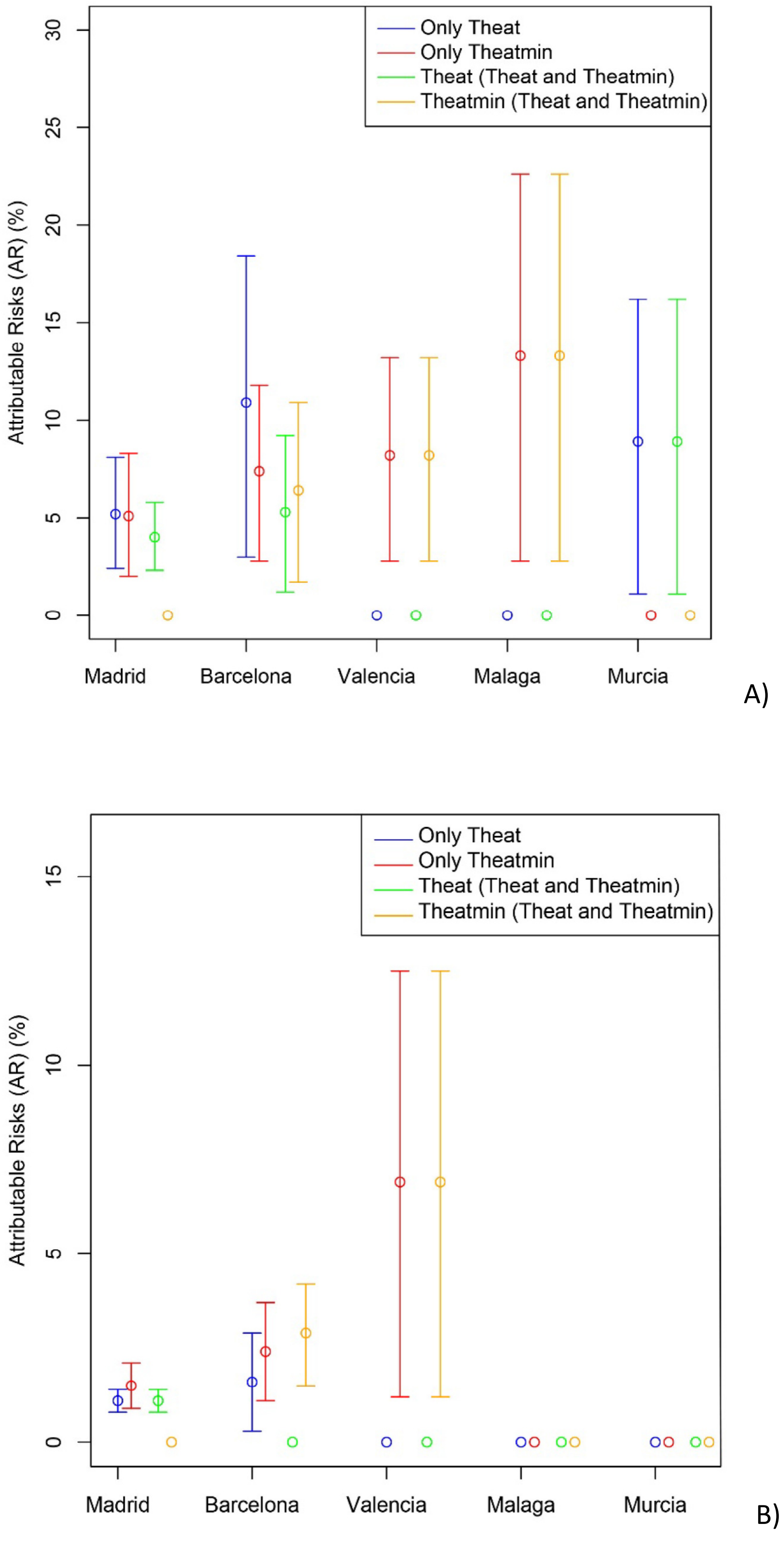

Fig. 3. Attributable risks (ARs) in models with Theat only (blue); and Theatmin only (red); and in models with Theat (green) and Theatmin (orange) for daily mortality (A) and emergency hospital admissions (B).

Table 5
Mortality and annual emergency hospital admissions attributable to the maximum daily temperature (Tmax), variable Theat, and minimum daily temperature (Tmin), variable Theatmin, with their respective 95 % CIs and percentage of deaths and admissions, both for GLM models in which Tmax only and Tmin only were included, and for models in which both were included.

	Theat only	Theatmin only	Theat and Theatmin
Madrid			
Deaths/year	264 (121410) **3.6 %**	88 (33164) **1.2 %**	**Theat** 115 (67165) **1.6 %**
Admissions/year	405 (296515) **0.7 %**	172 (103239) **0.3 %**	**Theat** 405 (296515) **0.7 %**
Barcelona			
Deaths/year	17 (5 28) **0.6 %**	18 (7 29) **0.6 %**	**Theat** 8 (112) **0.3 %** **Theatmin** 16 (4 26) **0.5 %**
Admissions/year	25 (5 45) **0.1 %**	64 (28 98**) 0.2 %**	**Theatmin**:76 (40110) **0.2 %**
Valencia			
Deaths/year	NA	13 (4 21) **0.7 %**	**Theatmin** 13 (4 21) **0.7 %**
Admissions/year	NA	140 (25253) **0.5 %**	**Theatmin** 140 (25,253) **0.5 %**
Malaga			
Deaths/year	NA	4 (1 7) **0.4 %**	**Theatmin** 4 (1 7) **0.4 %**
Admissions/year	NA	NA	NA
Murcia			
Deaths/year	3 (0 5) **0.3 %**	NA	**Theat** 3 (0 5) **0.3 %**
Admissions/year	NA	NA	NA

NA = No association.

would indicate that it is during the first heat wave of the year when there are more vulnerable persons, and that the susceptible population becomes gradually smaller as the summer progresses (Alberdi et al., 1998). On the other hand, the positive sign of the coefficients which link this variable to daily morbidity and mortality would indicate that the longer a heat wave lasts, the greater its impact (Díaz et al., 2002).

Lastly, the results in Table 5 relating to morbidity and mortality indicate very similar percentage values for all the cities, with Madrid having the highest heat-wave-related mortality as a consequence of the greater number of heat waves recorded and their intensity. The number of attributable deaths in the cities analysed is lower than that found in other studies (Díaz et al., 2015). The reason for this may be the reduction in the impact of heat in the period analysed (2013–2018) as compared to that of the previous study (2000–2009), but it may also be due to the fact that the current study was conducted at a city level, whereas Díaz et al.'s study was conducted at a provincial level. Furthermore, our study controlled for air pollution levels while Díaz et al.'s, 2015 study did not.

4.3. Limitations and strengths

The principal limitation of this study is that it was restricted to five Spanish cities, so that no conclusions can be extrapolated to Spanish cities as a whole. However, the condition requiring all the cities analysed to have one meteorological reference observatory within and another outside the city limits, is a trait that limited the number of cities in which this analysis could be carried out. Added to this are the limitations inherent in assigning exposure to meteorological variables to all citizens on the basis of data from a single observatory, despite its being situated within the city limits. Similarly, there are the epidemiological limitations inherent in any ecological longitudinal time-series study. Other aspects not covered by this study, which could presumably explain some of the heterogeneities observed, might be due to the population's unequal vulnerability and other socio-health characteristics (Arsad et al., 2022), something that has a directly proportional relationship with heat-related mortality (Achebak et al., 2018).

This study's main strength is that the meteorological data used are data observed at both urban and non-urban observatories, i.e., they are not data estimated on the basis of satellite observations as occurs with other studies (Iungman et al., 2023; Lehoczky et al., 2017; López-Gómez, 1993). The temperature recorded in these meteorological observatories better reflects the population exposure to the health risks derived from high temperatures. Furthermore, the estimates of the impact of heat waves on morbidity and mortality are based on models which were fitted for each city and in which numerous city-specific variables were controlled for, without results being extrapolated for ARs obtained in other studies (Martínez-Solanas et al., 2021).

4.4. Conclusions

This study's principal conclusion is the need to conduct studies at a local level, since it is these local factors which determine whether the UHI effect will have a greater or lesser impact on population health in a given city. Of the results obtained here, mention should be made of the fact that there are cities, non-coastal cities, where the UHI effect, which is indicated by Tmin, would have a relative importance with respect to daily morbidity and mortality, inasmuch as it is maximum daily temperatures which show this association. In coastal cities, in contrast, the UHI effect is more pronounced in its intensity and, in addition, is directly related to daily morbidity and mortality.

Hence, from the results of this study it cannot be concluded that minimum daily temperatures would show a greater impact on morbidity and mortality than would maximum daily temperatures, and that the UHI effect would be decisive in all cities when it comes to quantifying the heath impact of heat waves. Studies must be undertaken at a local level, if one is to achieve a population adaptation process to high temperatures within the context of climate change, which is based on scientific evidence, as urged by the WHO (WHO Regional for Europe, 2021).

CRediT authorship contribution statement

Teresa Cuerdo-Vilches. Providing and Analysis of data; Elaboration and revision of the manuscript.

Julio Díaz. Original idea of the study. Study design; Elaboration and revision of the manuscript.

José A López-Bueno. Providing and Analysis of data; Elaboration and revision of the manuscript.

M Yolanda Luna. Providing and Analysis of data; Elaboration and revision of the manuscript.

Miguel Ángel Navas. Providing and Analysis of data; Elaboration and revision of the manuscript.

Isidro J Mirón. Providing and Analysis of data; Elaboration and revision of the manuscript.

Cristina Linares. Original idea of the study. Study design; Elaboration and revision of the manuscript.

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to express their gratitude for the funding provided by the ENPY 304/20, and ENPY 436/21 projects of the Carlos III National Health Institute (ISCIII).

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