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Geographical Patterns in Mortality Impacts Due To Heatwaves of Different Characteristics in Spanish Cities

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Key Points:

- No general patterns found describing the heatwave characteristics-mortality association
- The heatwave characteristics-mortality coupling needs a local scale analysis due to its complex and strong dependence on local properties
- The health indices recovery factor and excess heat factor do not always represent the heatwave-mortality association

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The impact of heatwaves (HWs) on human health is a topic of growing interest due to the global magnification of these phenomena and their substantial socio-economic impacts. As for other countries of Southern Europe, Spain is a region highly affected by heat and its increase under climate change. This is observed in the mean values and the increasing incidence of extreme weather events and associated mortality. Despite the vast knowledge on this topic, it remains unclear whether specific types and characteristics of HW are particularly harmful to the population and whether this shows a regional interdependency. The present study provides a comprehensive analysis of the relationship between HW characteristics and mortality in 12 Spanish cities. We used separated time series analysis in each city applying a quasi-Poisson regression model and distributed lag linear and non-linear models. Results show an increase in the mortality risk under HW conditions in the cities with a lower HW frequency. However, this increase exhibits remarkable differences across the cities under study not showing any general pattern in the HW characteristics-mortality association. This relationship is shown to be complex and strongly dependent on the local properties of each city pointing out the crucial need to examine and understand on a local scale the HW characteristics and the HW-mortality relationship for an efficient design and implementation of prevention measures.

Plain Language Summary Heatwaves (HWs) are episodes of extreme heat sustained in time with devastating socio-economic impacts. Due to their global magnification, the interest in their impacts on human health has increased. Spain, in Southern Europe, is a climate change hot spot, particularly in relation to increasing temperature extremes. Despite the relevance of the topic, it is still unclear if there are particular characteristics of heatwaves with a larger impact on mortality. In the present study, we analyze the relationship between heatwaves' characteristics and mortality risk in 12 Spanish cities. Results show no general pattern for the relationship between mortality and heatwave characteristics over the 12 cities under study, but local relations point out the need for local studies to accurately assess the relationship between heatwave characteristics and mortality for an efficient implementation of prevention measures.

1. Introduction

Heatwaves (HW) are extreme events of high temperature that pose a threat to human health (Barriopedro et al., 2023; Khodayar & Paredes-Fortuny, 2024; Paredes-Fortuny & Khodayar, 2023). Spain, located in the western region of the Mediterranean Sea, is particularly affected by this phenomenon. The Mediterranean is a climate change hot spot warming 20% faster than other areas of the globe (Lionello & Scarascia, 2018; MedECC, 2020). The IPCC reports indicate that HWs will become more frequent and severe in the Mediterranean in the coming years (IPCC et al., 2021). A joint spatiotemporal investigation of the HWs in Spain, reveals a magnification of this phenomenon resulting from a growing population of the most extreme HWs (Paredes-Fortuny & Khodayar, 2023). Additionally, that analysis suggests that the most damaging HWs are not necessarily the most intense but can be extremely long-lasting or have a low recovery factor (Pereira et al., 2017, RF) stressing the importance of considering the overall HW characteristics when studying the association between HWs and mortality. That study also shows that there are relevant local differences in the HW characteristics. On the coast, HWs are of higher intensity but occur at a lower frequency. These local particularities must be considered when the impacts on the population are studied. In general, higher intensity and duration HWs' are expected in Spain in the future (Lorenzo et al., 2021; Viceto et al., 2019).

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Parallel to this, there is substantial evidence showing an increase in mortality associated with HWs in many areas of the globe (Ballester et al., 2023; Kollanus et al., 2021; Lo et al., 2022; Lopez-Bueno et al., 2020; Moraes et al., 2022; Ruiz-Páez et al., 2023; Ruuhela et al., 2020; Silveira et al., 2023; Yang et al., 2019). The European HW of 2003 was a record-breaking case, which was responsible for 70,000 additional deaths in Europe (Robine et al., 2008). Recent epidemiological investigations have shown that HWs, and more generally heat, are particularly impactful in the Mediterranean region (Zhao et al., 2021). Despite the recent efforts to protect the population from extreme heat, in the past summer of 2022 about 5,000 people died in Spain due to extreme heat (Tobías et al., 2023). In Madrid and Barcelona, the two most populated cities of Spain, heat has been responsible for about 16% and 22% of the hospitalisations resulting in death due to respiratory disease during the 2006–2019 period (Achebak et al., 2023).

During the last years, mortality associated with HWs in the Mediterranean area and Spain have shown a decrease in some cities (Díaz et al., 2018; Linares et al., 2015; Mirón et al., 2015) but an increase in others (Díaz et al., 2018). Several factors have been proposed, namely the introduction of heat-health prevention plans (Díaz et al., 2018), the income level which is strongly related to the existence of air conditioning units (Linares et al., 2015; Lopez-Bueno et al., 2020; Mirón et al., 2015), and the proportion of older adults which is reported as a risk factor (Arsad et al., 2022; Kollanus et al., 2021; Lopez-Bueno et al., 2020; McKenna et al., 2023). The large spatial heterogeneity of the heat-mortality association (Arsad et al., 2022; D'Ippoliti et al., 2010; Kang et al., 2020; Ruuhela et al., 2020) highlights the importance of understanding which factors are the most relevant to this association and how they are related to the mortality increase for the effective development of adaptation and protection plans.

Several previous investigations already examined the effect of heat and HWs on mortality in Spain (Carmona et al., 2017; Díaz et al., 2018; Roldán et al., 2016; Royé et al., 2020). However, current knowledge does not consider the changes in the mortality risk associated with different combinations of the HW duration with the HW intensity, minimum temperature, excess heat factor (EHF, Nairn & Fawcett, 2014), and RF (Díaz et al., 2018; Linares et al., 2015; Miron et al., 2015). Moreover, the later indices, EHF (Excess Heat Factor; Nairn & Fawcett, 2014, EHF) and RF (Recovery Factor; Pereira et al., 2017, RF) are widely used in meteorology, but a quantitative evaluation of their adequacy to describe the increase in mortality in different climatic, demographic, and socioeconomic conditions is lacking. The EHF measures the HW severity taking into account the human climatization capability by considering the recent past temperatures as a reference. The RF quantifies the thermal comfort considering nighttime temperatures which are related with the capacity of the human body to recover from the exposure to daytime high temperatures. To the authors' knowledge, this is the first analysis addressing these two aspects using a set of HWs identified with a common definition from the Spanish MetService, AEMET. The present analysis at the city scale includes 12 province capitals covering several decades, different climates, and population densities. This evidence would help improve preparedness for future HW events by adapting current mitigation and prevention measures to the singularities of the local-scale HW impacts (Linares et al., 2015; López-Bueno et al., 2020).

2. Data and Methodology

2.1. Area of Study and Data Collection

The study was performed independently in 12 Spanish province capitals (Figure 1a). The ensemble of cities illustrates a diversity of climates and conditions in Spain, with coastal and inland, Mediterranean and Atlantic, lower and higher population density cities (see Table S1 in Supporting Information S1 for more details of the cities' climatology). Time series of daily all-cause mortality data of the 12 studied cities was collected from Instituto Nacional de Estadística (INE, Spanish Statistics Institute). Mortality data consists of the reported daily mortality due to all causes in each city for the extended summers (May–September) from 1975 to 2019. A description of the mortality data, in terms of total mortality and mortality rate (per 105 inhabitants) is provided in Table S1 and Figure S1 of the Supporting Information S1.

Daily maximum and minimum temperatures (Tmax and Tmin, respectively) were retrieved from the ROCIO_IBEB data set, a 5 km gridded observational data set covering peninsular Spain and the Balearic Islands from Agencia Estatal de Meteorología (AEMET, Spanish MetService). This data set includes information on 2-m Tmax and Tmin obtained from the interpolation of the data derived by 1,800 thermometric stations covering Spain and the Balearic Islands with the climatology. The climatology used for the interpolation is based on the

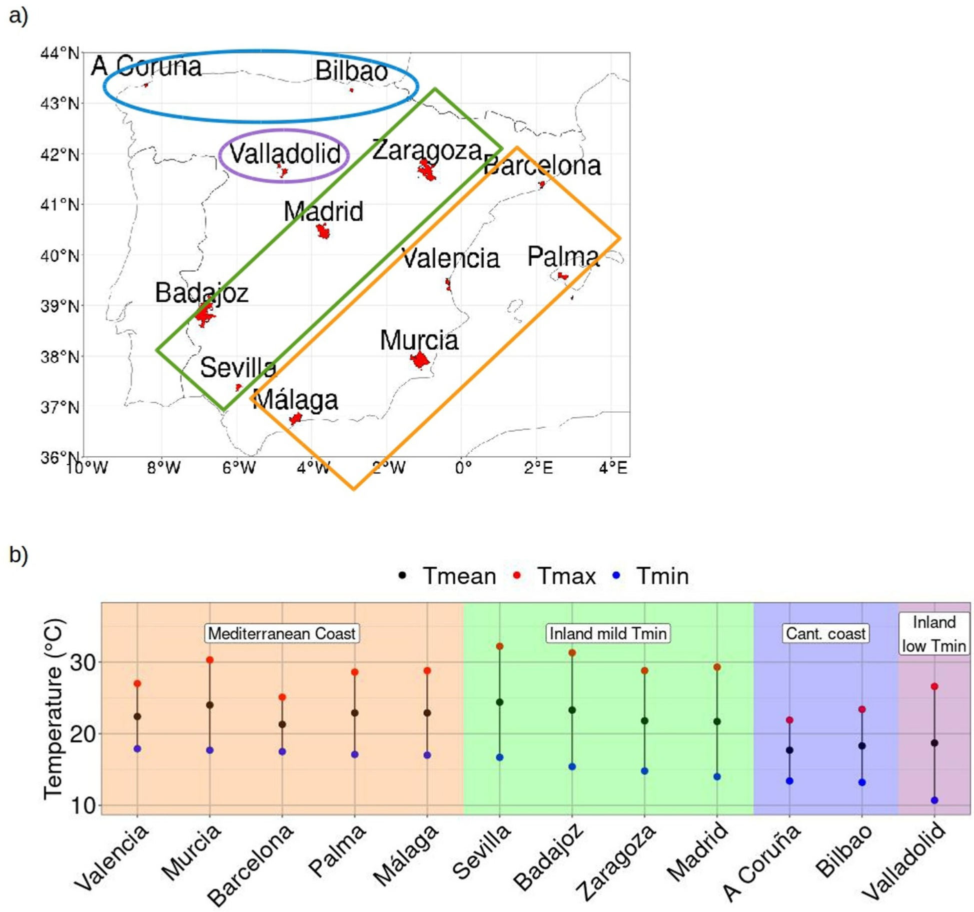

Figure 1. (a) Cities under study grouped by climatological and geographical characteristics: Mediterranean coast (orange), Inland mild Tmin (green), Cantabrian Coast (blue), and Inland low Tmin (purple). (b) For each city (*x*-axis), daily minimum (blue), maximum (red) and mean (black) temperature (Tmin, Tmax, and Tmean respectively). Background shadow indicates the aforementioned groups to which each city belongs.

historical analysis of the numerical prediction model HIRLAM. Further details regarding this data set can be consulted in Amblar-Francés et al. (2020). Daily mean temperature (Tmean) is approximated as the mean of Tmax and Tmin. The temporal range of the data used in the present study covers the extended summers (May–September) from 1975 to 2019. Considering the summer mean daily minimum temperature and the geographical location (inland/coast) of each city, four groups are identified namely the Mediterranean coast, the Inland mild daily minimum temperatures, the Cantabrian coast and the Inland low daily minimum temperatures (Figure 1b).

2.2. Heatwave Identification and Characterization

In the present study, HWs were defined following the Spanish Meteorological Service, AEMET, definition (AEMET. Olas de calor en España des de, 2023) as an event in which for at least 3 consecutive days Tmax exceeds the 95th percentile (P95) and affects at least 5% of the area under study. The 5% spatial threshold is used following the approach of Paredes-Fortuny and Khodayar (2023), a comprehensive analysis of the HW phenomena over Spain. Following the HW identification methodology of Paredes-Fortuny and Khodayar (2023), HWs were computed at each grid point of Peninsular Spain and the Balearic Islands (PSBI) for each day of the period under study, extended summers (May–September) from 1975 to 2019. P95 was computed at each gridpoint of PSBI using the Tmax time series of the climatological reference period, May–September 1961–1990, following the WMO recommendations (World Meteorological Organization, 2017). The days that make up a HW are named HWD. Thus, a daily time series of HWD occurrences was obtained for each grid point. Afterward, the HWD time series of the grid points contained in each city were aggregated into a unique time series for each city.

Table 1
Definitions of the Variables Used in This Study and Their Corresponding Units

Variable name	Definition	Units
HW	Three or more consecutive days with Tmax > P95 affecting 5% of PSBI	Event
HWD	Day t that conforms a HW	Days
HWD Intensity[a]	$\text{Tmax}(t) - P95$	°C
HWD Cumulative duration	Days after the HW onset plus one	Days
HWD Tmin[a]	$\text{Tmin}(t)$	°C
HWD Excess heat factor (EHF, Nairn & Fawcett, 2014)[a]	The EHF is a measure of the HWD severity regarding the magnitude of the intensity and how sudden the temperature rise is $\text{EHI}_{sig}(t) = \frac{T(t)+T(t+1)+T(t+2)}{3} - P95$ $\text{EHI}_{acc}(t) = \frac{T(t)+T(t+1)+T(t+2)}{3} - \frac{T(t-1)+\ldots+T(t-30)}{30}$ $\text{EHF}(t) = \text{EHI}_{sig}(t)\cdot\max(1, \text{EHI}_{acc}(t))$	°C^2
HWD Recovery factor (Karl & Knight, 1997; Pereira et al., 2017)[a]	Measure of human thermal comfort. $\text{RF}(t) = \text{Tmax}(t) - \text{Tmin}(t)$	°C
HWD level	Classification of the HWD indicating the magnitude of the HWD's temperature variables (i.e., intensity, Tmin, EHF, and RF) in combination with the magnitude of the cumulative duration	Unitless

[a]This is the definition for each gridpoint. The corresponding HWD' value is the mean of the city gridpoints affected by the HW on this day.

The obtained HWDs of each city were then characterized independently by their intensity, cumulative duration, and daily minimum temperature (Tmin). Additionally, two health indices namely the excess heat factor (EHF, Nairn & Fawcett, 2014) and the recovery factor (RF, Pereira et al., 2017) were calculated. Table 1 shows the definitions of the above-mentioned HW characteristics and health indices. On a later step and independently for each city, HWDs were classified into levels that indicate the value of each of the HWD's temperature-related variables (i.e., intensity, Tmin, EHF, and RF) in combination with the value of the cumulative duration as follows. Each HWD is given one label for each HWD variable namely intensity, Tmin, RF, EHF, and cumulative duration that can be >P50 or <P50 indicating if the value of the variable is above (>P50) or below (<P50) the 50th percentile of the given city. The threshold was set at 50% to ensure both groups had the same number of HWDs. Afterward, independently for each temperature-related variable (i.e., intensity, Tmin, EHF, and RF), four possible levels were obtained resulting from the combination of the two possible labels of the magnitude of the temperature-related variable and the two possible labels of the cumulative duration. In parallel, HWs were classified into 16 typologies regarding the simultaneous values of the HW' Tmax, Tmin, intensity and duration (the number of days that the HW lasts over a city). These typologies are the combination of high/low values of each of these four HW variables. The threshold used to classify HWs as high or low regarding each variable is the 50th percentile of the HWs of all cities. Thereafter, the number of occurrences and the proportion of each HW type in each city was computed. The detailed description of each HW typology and its frequency in each city is shown in Figure S2 of the Supporting Information S1.

2.3. Assessment of the Heat-Mortality Association

To estimate the heat-mortality association, we applied state-of-the-art epidemiological methods consisting of separate time-series analyses in each city. The analysis is restricted to the extended summer months (i.e., from May to September). Daily mortality was modeled as a discrete random variable that follows a quasi-Poisson distribution. That is a discrete random event with a large sample space whose estimated value is larger than its variance. Three models have been used to evaluate the HW-mortality association with increasing complexity. The mathematical definitions of the models and their terms are shown in the detailed description of the models section of the Text S1 in Supporting Information S1. All of them include a temporal term ($X_t(t)$) which controls seasonal and long-term patterns in the outcome with a natural spline (ns) of time with one degree of freedom per year, a natural spline (ns) of the day of the year (doy) with four degrees of freedom, and an indicator of the day of the week (dow). The heat-mortality association was modeled using distributed lag linear and non-linear models (DLM, DLNM) (Gasparrini et al., 2010) to account for potential lagged effects up to 3 days. In the first model,

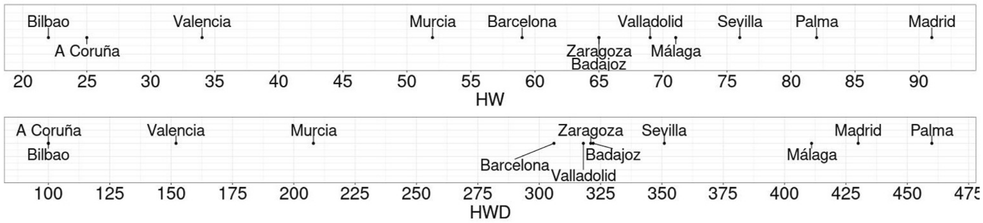

Figure 2. For each city, the sum of the number of heat waves (HW) and heat wave days (HWD) identified in the period from May to September 1975 to 2019.

named the overall HW effect (Y_{HW}), HW's occurrence was modeled with a binary variable, $X_{\mathrm{HW}}(t)$, thus the β coefficient corresponds to the mortality risk associated with HW occurrence. In the second model, named the additive HW effect model ($Y_{\mathrm{Tmean+HW}}$), Tmean was introduced with the term $X_{\mathrm{Tmean}}(t)$, modeled with a DLNM consisting of a natural spline with two knots placed at the 50th and 90th percentiles of the city's Tmean and a lag of 3 days modeled with strata function (i.e., 0 and 1–3 lags). Thus, in this case, the β coefficient of the $X_{\mathrm{HW}}(t)$ represents the additive effect associated with HW event (i.e., more than 2 days of high temperatures) on top of the effect of Tmean (i.e., high temperatures). The choice of 3 days is widely used in literature since it has been found that after 3 days the effect of heat on mortality decays (Guo et al., 2017; Huang et al., 2014). The third model, named the HW variable model (Y_{HWvar}), is analogous to the second model replacing the term $X_{\mathrm{HW}}(t)$ with a categorical variable indicating the HWD level, $X^{i}_{\mathrm{level}}(t)$. The HW variable model was applied independently four times, one for each of the following HWD variables intensity, Tmin, RF, and EHF. For each of these four HWD variables, there are four possible values of the term $X^{i}_{\mathrm{level}}(t)$ that are the combination of the two possible labels of the cumulative duration (<P50/>P50) with the two possible labels of the given HWD variable i (<P50/>P50) (where i = intensity, Tmin, RF, and EHF).

The modeling has been done with the R package *dlnm* (Gasparrini, 2011). The association between mortality and the different model components has been reported as relative risk (RR), with the days without HW (non-HWD) as a reference. The RRs associated with each of the model terms HW' occurrence ($X_{\mathrm{HW}}(t)$) and HWD' level ($X^{i}_{\mathrm{level}}(t)$) was computed as $\mathrm{RR}_k = e^{\beta_k}$, where k = HW, level$i$ and β_k is a numerical value obtained from the *glm* model. Akaike Information Criterion (AIC) tests have been done changing the degrees of freedom of the natural splines.

3. Results

3.1. HWs Over Spanish Cities

During the extended summers (May–September) between 1975 and 2019, from 22 to 91 HWs were identified in the 12 cities under study. The lowest HW/HWD frequencies (number of HWs/HWDs per year), up to 59 HWs/310 HWDs, were found in the coastal cities of Bilbao, A Coruña, Valencia, Murcia, and Barcelona. Except for Murcia, these cities presented the largest mortality rates, ranging from about 15,000 to 17,500 deaths/10^5 inhabitants in A Coruña and Bilbao, respectively (Figure 2). The analysis of the HW characteristics occurring in each of the 4 climatological groups (Figures S2 and S3 in Supporting Information S1) namely the *Mediterranean coast* (Barcelona, Málaga, Murcia, Palma, and Valencia), the *Cantabric coast* (A Coruña and Bilbao), *Inland mild daily minimum temperature (Tmin)* (Badajoz, Madrid, Sevilla, and Zaragoza) and *Inland low Tmin* (Valladolid), reveals that the HWs affecting each climatological group were similar. Generally, HWs belonging to the upper 50th percentile of Tmax occur in the Inland mild group and in Murcia (Mediterranean coast group). In contrast, HWs in the Mediterranean and in the Cantabric coasts and in Valladolid belong to the lowest 50th percentile of Tmax. Interestingly, the HWs affecting the Mediterranean coast group are also of large Tmin (the upper 50th percentile of Tmin) while in Valladolid and in the Cantabric coast group are of low Tmin. The largest durations (the number of days that last a HW) were found in Málaga and Palma. Large differences (up to 10°C) were found in the median values of the RF during HWDs, while the EHF presents a median value between 3 and 5°C^2, except for Bilbao where 13°C^2 were observed during HWDs.

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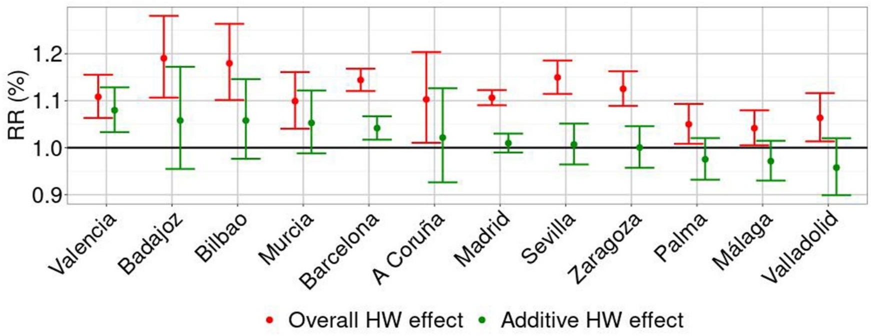

Figure 3. Relative risk (RR) associated with the HW occurrence derived from the overall HW effect model (Y_{HW}, red points) and the additive HW effect model ($Y_{Tmean+HW}$, green points). Error bars indicate 95% confidence intervals. Mortality reference is non-HWDs. The horizontal black line at RR = 1 indicates the threshold above which there is larger mortality associated with HWDs compared with non-HWDs.

3.2. Effect of HWs on Mortality

3.2.1. Association Between HW Occurrence and Mortality

According to the overall HW effect model (Y_{HW}), HW's occurrence was associated with an increase in mortality risk (RR > 1) in all the cities (Figure 3, red points). In this model, the daily mean temperature was not included. This increase in the mortality risk presents large differences between cities even within the same climatological group (Figure 1). During HWDs, mortality risk increased from 4.2% [95% CI 0.5, 7.9] in Málaga up to 19.0% [95% CI 10.7, 28.1] in Badajoz (Figure 3, red points), compared to non-HWDs. Confidence intervals were larger in less populated cities such as Badajoz, A Coruña, Valladolid, and Bilbao.

3.2.2. Additive Effect of HW Occurrence on Temperature (Tmean + HW)

The independent or additive effect of the HW occurrence on top of Tmean is the effect associated with the HW occurrence when Tmean is included in the model (additive HW effect model, $Y_{Tmean+HW}$). The mortality risk associated with the additive effect of the HW occurrence increased (RR > 1) in the cities with the 6 lowest HW' frequency, namely Valencia, Bilbao, Murcia, Barcelona, A Coruña and Badajoz. This risk ranged from 4.2% [95% CI 1.7, 6.7] in Barcelona up to 8.0% [3.3, 12.8] in Valencia (Figure 3, green points). These cities with RR > 1 are coastal except for Badajoz. However, the RR decreased in all cities compared to the overall HW effect model (Figure 3, red points).

3.2.3. Additive Effect of HW Characteristics

In the following step, the influence of the intensity/Tmin/RF/EHF combined with the cumulative duration was assessed with the HW variable model (Y_{HWvar}). Four possible levels result from the combination of the two possible labels of the cumulative duration (above/below the 50th percentile) and the two possible labels of the other given HWD variable (above/below the 50th percentile). Figure 4 shows the RR obtained when considering the cumulative duration together with the other four HWD variables (i.e., intensity, Tmin, RF, and EHF) resulting in different patterns for each city.

Generally, an increase in the mortality risk associated with some levels was observed in the cities that already showed an increase in the mortality risk associated with the additive effect of the HW occurrence on top of the effect of temperature (additive HW effect model). These correspond to cities with low HW frequency (A Coruña, Badajoz, Barcelona, Bilbao, Murcia, and Valencia).

Overall, in some cases detailed in Table S2 of the Supporting Information S1, the most dominant characteristic in the increase/decrease of the mortality risk seemed to be the cumulative duration, while in some others it was the intensity/Tmin/EHF/RF or a specific combination of high/low values of the cumulative duration and the intensity/Tmin/EHF/RF. As in illustration, in Valencia (except for HWD-EHF) and Murcia (except HWD-Tmin) changes in the cumulative duration level (above/below P50) did not lead to substantial changes in the mortality risk. In contrast, different cumulative duration levels led to different RRs under the same Tmin level in cities such

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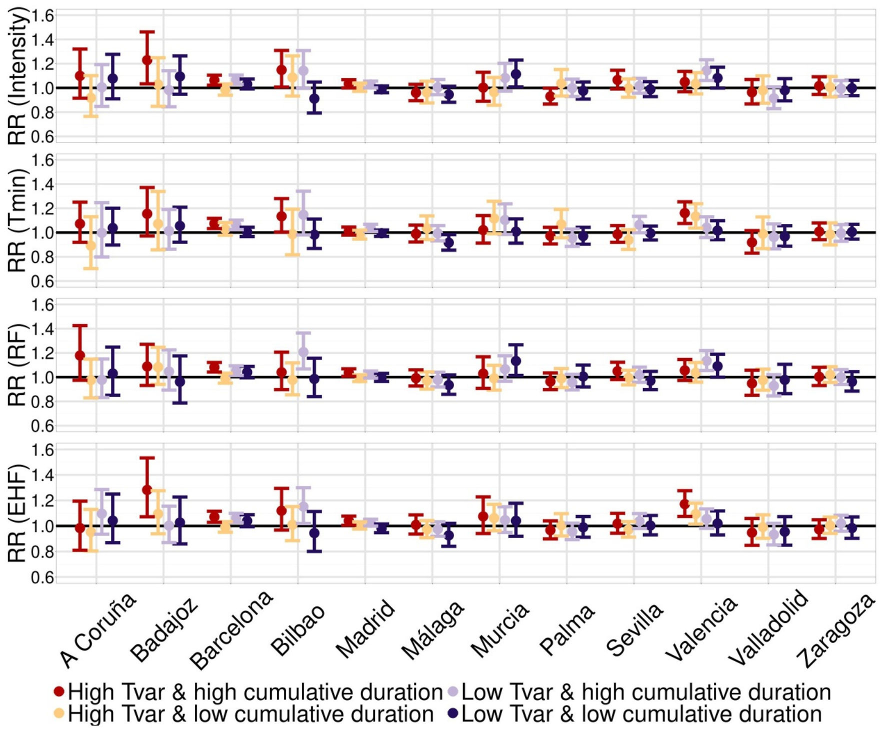

Figure 4. For each city (*x*-axis), the relative risk (RR) is associated with each HWD (heatwave day) level. Levels are the combination of the HWD's cumulative duration and another HWD's variable (in the following, the set of these other temperature related HWD variables are referred to as Tvar), from top to bottom: HWD's recovery factor (RF), HWD's intensity, HWD's minimum temperature (Tmin), HWD's' excess heat factor (EHF). Each HWD variable is divided into two groups corresponding to values above/below the 50th percentile (P50) of the corresponding city. This subdivision results in four subgroups for each combination of cumulative duration and another Tvar. The groups above/below P50 are described as high/low values in the legend using a bivariate color scale (warm colors (red and yellow) indicate high values of Tvar while cold colors (light and dark purple) indicate low values of Tvar). Red: both Tvar and cumulative duration above P50 (high), yellow: Tvar above P50 (high) and cumulative duration below P50 (low), light purple: Tvar below P50 (low) and cumulative duration above P50 (high), dark purple both Tvar and cumulative duration below P50 (low).

as Bilbao. In this city, increased mortality associated with HW was only observed in periods of long duration, regardless of the intensity of the event (except for RF). Badajoz is an example of a pattern consisting of an increase/decrease of the mortality risk only with a certain combination (Figure 4, fourth row, second column). In Badajoz, an increase in the mortality risk was observed only in HWDs with a simultaneous high EHF (>P50) and a large (>P50) cumulative duration meaning that the risk of mortality only increased after several days of HW conditions in which these latest HWDs had a high EHF (>P50).

4. Discussion

This study presents an analysis of the mortality risk associated with HW occurrence and depending on different HW characteristics in 12 province capital cities over Spain. Additionally, the effectiveness of the meteorologically widely used health indices EHF and RF to represent the HW-mortality relation has been examined. To our knowledge, this is the first assessment that analyses the mortality risk associated with different combinations of characteristics and health indices of an evenly identified set of HWs. The HWs analyzed in this study were identified in a common framework using the Spanish MetService (AEMET) definition. We identified and characterized HWs using the observational temperature gridded data set from AEMET at 5 km resolution and daily observations of mortality from 12 Spanish cities. This investigation covers a wide range of climates and population densities over Spain for the period of the extended summer months (May–September) from 1975 to 2019. We employed three distributed lag non-linear epidemiological models of increasing complexity.

Overall, our findings revealed no general patterns on how HW characteristics affect mortality in the studied cities. Due to this variation, these results may not be broadly applied to other Spanish cities, stressing the need for additional local studies.

Our study reveals an increase in the mortality risk associated with the HW occurrence in the cities with the lower HW frequencies namely Valencia, Badajoz, Bilbao, Murcia, Barcelona, and A Coruña. This increase in the mortality risk is the additive or independent effect of the HW occurrence on top of the effect associated with the presence of high temperatures. This subset of cities presents different summer temperatures and the typology of HWs affecting these cities is diverse. Except for Badajoz, these cities share a coastal location. Nevertheless, the temperatures registered on the Cantabrian coast are much lower than the Mediterranean coastal temperatures. The low HW frequency is a common feature for these cities that is not found in the other studied cities. Consequently, the HW frequency could be a factor influencing the mortality risk response to the HW occurrence. The cities with a larger HW frequency are more frequently exposed to high temperatures and may have certain adaptations, both in the population and in the city. These cities may have better-prepared infrastructures to face high temperatures. Besides, their population may have a higher awareness degree of the threat that such events pose to human health and may be more acclimatized in contrast to the cities where HWs are rare events. Another factor may be the fact that Valencia, Bilbao, Barcelona, and A Coruña also present the largest mortality rates of the cities under study.

The association between mortality risk and each HW variable did not follow a homogeneous pattern among the 12 cities examined. Each city presented a particular response to the influence of the cumulative duration combined with the intensity, minimum temperature, Excess Heat Factor or Recovery Factor on the mortality risk.

The expected performance of the health indices EHF and RF according to their definitions was an increase in the relative risk of mortality with respectively larger or lower values of the corresponding index.

This relationship was not found in all the cities. This indicates that the suitability of the EHF and the RF to assess the association between HWs and mortality in each city may be limited to cities meeting particular conditions. These conditions are probably similar to the conditions found in the cities where the RF and EHF represent the increase in mortality risk according to their definition. These cities are the Mediterranean coastal city of Valencia for the RF, and the inland city of Badajoz and Valencia for the EHF. This conclusion is particularly relevant given the recent extensive use of these indices in the scientific community to evaluate the health-related impact of HW occurrence.

As an illustration, in Valencia, the dominant characteristic in the HW-mortality relation is the increasing Tmin, and the consequent reduction of the Tmax Tmin difference, thus the reduction of the RF. In this city, the RF will show an accurate representation of the mortality risk increase given that the RF considers the response of the human body to Tmin. It is still unclear why the RF presented a different relationship with the mortality risk in other cities such as Barcelona, with similar coastal locations, climatic conditions and HW typologies. Besides, in Badajoz, where long-lasting HWs of large Tmin are associated with an increase in the mortality risk, similarly to Valencia, low values of the RF are not associated with an increase in the mortality risk.

The EHF considers the acclimatization capability of the population quantifying the intensity of sudden temperature rises. Its best performance in assessing the association between mortality and HWs was found in Valencia and Badajoz. Generally, HWs affecting Badajoz are of high Tmax and some are of simultaneously high Tmax, Tmin and intensity, contrasting with the abovementioned HW typology for Valencia. It is interesting to note that Badajoz had a similar climate and HW typology as Madrid, Sevilla, and Zaragoza where an increase in the relative risk of mortality was not observed for high EHF.

Several factors could be involved in these differences such as differences in the age distribution of the population, different population densities and mortality rates, different climates and HW typologies affecting the cities. These climatological and sociological differences may lead to a different acclimatization capability of the population. These results expose the complexity of the association between HWs, and mortality and the explanation of these differences requires detailed investigation at a local scale. A distinctive effect of the HW characteristics in different areas of the same country was also observed in Korea between rural and urban areas (Kang et al., 2020) and in Finland in Helsinki compared to its surroundings (Ruuhela et al., 2020).

Our analysis poses one step forward in analyzing the temperature-mortality relationship in Spain concerning the high-resolution temperature data set employed in conjunction with the robust modeling applied that considers different HW characteristics. Nonetheless, some limitations still are identified, such as the limited number of selected cities, or the use of all-cause mortality data instead of cause-specific mortality data, which would produce more accurate results. Moreover, in a future study, it would be advisable to consider changes in mortality risk over time, which have not been explored here, following Ordanovich et al. (2023) finding adaptability to extreme heat in the most recent decades in Spain associated with a decrease in the mortality risk attributable to extreme heat from 0.8% to 0.5% since 1988–1999.

5. Conclusion

The main conclusion of the study is that an analysis at the local scale is needed to correctly understand the relationship between mortality and the different HW characteristics and health-related indices RF and EHF because no general relationship has been found.

Second, in our sample, the largest mortality risks associated with the HW occurrence are observed in the cities with the lower HW frequency. This increase in the relative risk of mortality is the independent or additive effect of the HW occurrence on top of the effect of high temperatures. However, a detailed analysis is needed in each city given the fact that the factors involved in this finding may vary across the cities.

Third, the health indices widely used, the RF and the EHF, do not always adequately represent the relation between HW occurrence and mortality. This concerns the intrinsic relation found between the characteristics of the HWs and the related mortality which is different in each city. These differences could be due to several factors such as the local climatology, the characteristics of the HWs affecting the cities, the demography, the socioeconomic level, or the adaptation measures to high temperatures implemented in the city. A more profound understanding of the factors involved in the relationship between these health indices and mortality is needed to understand the reason behind their distinctive performance in cities with similar HW typologies and climates.

The results presented in this work contribute to an improved understanding of the extreme heat-health relation at a regional-to-local scale. These findings further aid in the development of improved public health strategies to protect the Spanish population from extreme heat at a local scale. Particularly, the accurate implementation of efficient heat-health warning systems adapted to the local particularities would enhance the capacity to respond to these extreme events. Despite the crucial knowledge gained in this study, a more detailed analysis of the influence of the Urban Heat Island (UHI) effect and the large thermal variability identified in the cities will be necessary to complement our understanding of the extreme heat-mortality relationship. Further investigations addressing to what extent the different factors are contributing to the relationship between HWs and mortality are needed. The city-specific particularities found in the present study reinforce the need for an assessment of the HW-mortality association in other cities of Spain but also other populated areas of the globe suffering an intensification of the HW phenomena. A recent study analyzing the local evolution of the HWs over Europe reveals that HWs affecting Germany, the Netherlands and Belgium have become more intense and present larger values of the EHF, thus a larger impact on human health, in the last decades accompanied by a large variability across the continent (Khodayar & Paredes-Fortuny, 2024) exposing the increasing threat of HWs over Europe.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data set ROCIO_IBEB of daily maximum and minimum temperature was freely downloaded from AEMET (Agencia Española de Meteorología, https://www.aemet.es/en/serviciosclimaticos/cambio_climat/datos_diarios?w=2). Daily records of mortality from 12 Spanish cities were requested at INE (Instituto Nacional de Estadística).

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