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Modelling of Temperature-Attributable Mortality among the Elderly in Lisbon Metropolitan Area, Portugal: A Contribution to Local Strategy for Effective Prevention Plans

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Abstract Epidemiological studies on the impact of determining environmental factors on human health have proved that temperature extremes and variability constitute mortality risk factors. However, few studies focus specifically on susceptible individuals living in Portuguese urban areas. This study aimed to estimate and assess the health burden of temperature-attributable mortality among age groups (0–64 years; 65–74 years; 75–84 years; and 85+ years) in Lisbon Metropolitan Area, from 1986–2015. Non-linear and delayed exposure–lag–response relationships between temperature and mortality were fitted with a distributed lag non-linear model (DLNM). In general, the adverse effects of cold and hot temperatures on mortality were greater in the older age groups, presenting a higher risk during the winter season. We found that, for all ages, 10.7% (95% CI: 9.3–12.1%) deaths were attributed to cold temperatures in the winter, and mostly due to moderately cold temperatures, 7.0% (95% CI: 6.2–7.8%), against extremely cold temperatures, 1.4% (95% CI: 0.9–1.8%). When stratified by age, people aged 85+ years were more burdened by cold temperatures (13.8%, 95% CI: 11.5–16.0%). However, for all ages, 5.6% of deaths (95% CI: 2.7–8.4%) can be attributed to hot temperatures. It was observed that the proportion of deaths attributed to exposure to extreme heat is higher than moderate heat. As with cold temperatures, people aged 85+ years are the most vulnerable age group to heat, 8.4% (95% CI: 3.9%, 2.7%), and mostly due to extreme heat, 1.3% (95% CI: 0.8–1.8%). These results provide new evidence on the health burdens associated with alert thresholds, and they can be used in early warning systems and adaptation plans.

Keywords Mortality · Elderly · Extreme temperatures · Attributable risk · Distributed lag non-linear model (DLNM) · Portugal

Introduction

Several previous studies have reported an association between extreme temperatures and human mortality counts [1–14]. The greatest impact on mortality is visible among the elderly population, who are particularly vulnerable compared to younger people [15–19]. Extreme heat or cold events with greater magnitude and intensity may contribute to higher morbidity or mortality due to heat- and cold-related illnesses [20–23]. These illnesses are expected to be more severe among the most defenseless populations [24–27]. The elderly are often at higher risk due to limited mobility, susceptibility to infectious diseases, reduced caloric intake, and social isolation [18, 22, 24, 28, 29]. To protect human health, it is urgent to effectively address these risks that depend on geographic location, levels of socioeconomic

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development, resilience, and vulnerability, in a context of rapid climate change and demographic transition [1, 9, 30–32]. Populations in the WHO European region are particularly at risk because of the high proportions of elderly people living in urban areas [6]; however, if long-term measures are implemented at an early stage with regards to housing, energy, and the urban sector, the reduction of heat–health effects will be more effective [33].

The population structure of today's society is changing as the proportion of elderly people increases [34–37], resulting in a higher prevalence of chronic diseases, degenerative diseases, and mental illness [38, 39]. Persons aged 65 or over constitute the world's fastest growing age group [36]. According to the Organisation for Economic Co-operation and Development (OECD) [40] and Statistics Portugal (INE) [41], Portugal has one of the oldest populations in Europe and the world; in 2018, more than two million people were older than 65 years, in a total of 10.3 million inhabitants. On average, the share of the population aged 65 and over is projected to continue its increase in the coming decades, and those aged over 65 will exceed to over a third of the population by 2050 [40, 41]. Thus, scientific evidence on population and weather-related health risks could reinforce existing knowledge and support policy makers in developing appropriate strategies to protect elderly people and adopting measures to promote active aging [1, 38, 39, 42, 43].

Accordingly, the objective of this study was to assess the health burden of mortality attributable to temperature extremes in Lisbon Metropolitan Area (LMA), from 1986 to 2015. To the best of our knowledge, this study is the first to investigate long-time series effects of both cold and hot temperatures on mortality with minimum mortality temperature (MMT) among specific vulnerable groups in Portugal, according to age (0–64 years; 65–74 years; 75–84 years; and 85+ years). This study is important because (1) its subject is timely and the location of the research area has not been well studied to date; and (2) information on risk characterization and communication about who is most at risk are needed in order to establish and identify thresholds, and to update scientific information on particularly susceptible groups and health impacts.

Materials and Methods

Study Area

Lisbon Metropolitan Area (LMA) is the main metropolitan area of Portugal, comprising 18 municipalities and 211 civil parishes. The LMA represents 3.3% of the country's territory (3015.24 km^2) (red delimited area in Fig. 1). It concentrates approximately 27% of the Portuguese population, thus corresponding to a densely populated region (~940 inhab/km^2). According to Statistics Portugal (INE - Portuguese National Statistics Institute), this is the most densely populated metropolitan area in the country; in 2018, its resident population was 2,846,332 inhabitants, 21% of which were older than 65 years. The climate of the region is classified as having a dry and warm-summer Mediterranean climate (Csa, according to the Köppen-Geiger classification), with mild and wet winters.

Data Sources

Health Data

Death counts were obtained from Statistics Portugal (INE - Portuguese National Statistics Institute). Based on expected risk groups, the time series was disaggregated by four age groups [0–64 years; 65–74 years; 75–84 years; and 85+ years], for the period between January 1, 1986, and December 31, 2015. Mortality data are represented by daily deaths from all causes, excluding external causes, i.e., natural mortality [International Classification of Diseases, 9th revision (ICD-9) codes 0-799, and 10th revision (ICD-10) codes A00-R99].

Temperature Variables

Daily temperatures (daily-average, maximum, and minimum) for the time period 1986–2015 were obtained from NOAA's National Climatic Data Center (NCDC), specifically from the Meteorological Station in Lisbon: 85790 Gago Coutinho (represented by the star in the Fig. 1). Temperature data used for Lisbon is recorded by a meteorological station which is part of the national meteorological network run by the national weather service, Instituto Português do Mar e da Atmosfera (IPMA), and obeys to criteria imposed by the World Meteorological Organization in terms of data recording,

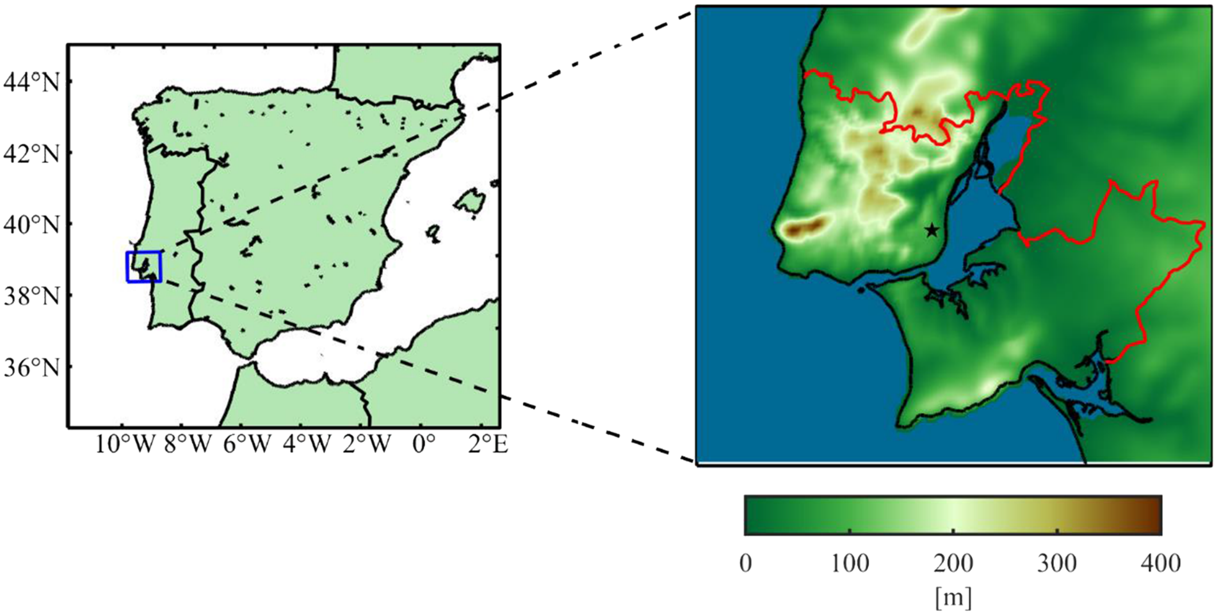

Fig. 1 Region of study. The Lisbon Metropolitan Area (LMA) is the area delimited by the red line. The topography is shown in the left figure. The star represents the meteorological station of Lisbon: Gago Coutinho

data quality, and representativeness of the region. These data have been already used in other studies [i.e., 2].

Statistical Analysis

Preliminary Analysis

Descriptive summaries such as mean, median, standard deviation, and quartiles were used to describe continuous variables (temperature and mortality counts). Additionally, the Excess Mortality for Winter versus Summer (EMWS) Index was used to investigate excess winter deaths against excess deaths during the summer [44, 45]. The EMWS index is the percentage change in reported death counts in the winter compared with the adjusted death counts during summer [44, 45].

Modelling the Temperature–Mortality Relationship

The effects of daily temperature on mortality in Lisbon Metropolitan Area (LMA) were estimated separately for winter (December–March) and summer (June–September) months and for each age group (0–64 years; 65–74 years; 75–84 years; and 85+ years). A semiparametric quasi-Poisson regression model accounting for overdispersion was used to investigate the temperature–mortality relationship, using distributed lag non-linear models (DLNM) [1–3, 27, 45–47, 48].

The model is of the following form:

$$LogE(Y_t) = \propto + ns\left(Date, \frac{df}{year}\right) + DOW_t + Holiday_t + cb\left(x_{t-l,}\beta_l\right) \quad (1)$$

where Y_t represents the expected number of deaths on day t; $\propto$ is the intercept; $ns(Date, df/year)$ is the natural cubic spline to capture long temporal trend (Date) with 2 degrees of freedom (df) per year; DOW_t represents a binary indicator of the day of the week, and holiday (Hoy) is the binary indicator whether day t is a public holiday or not. The $cb(x_{t-l,}\beta_l)$ term is the cross-basis function of daily temperature and describes the dependency of the relationship along the daily temperature x_t and lag effects, l days.

Previous studies [49, 50, 51] have suggested that temperature–mortality relationships may not be linear and often exposure–response spreads over a few periods. Therefore, the cross-basis function $b = \int_{l_0}^{21} f.w(x_{t-l}) \approx \sum_{l=l_0}^{21} f.w(x_{t-l}, l) = w_{x,t}^T$, involving a tensor product between the basis chosen for temperature–mortality function, $f(x)$, and lag–mortality function, $w(l)$, was used to examine simultaneously the non-linear and lag effects of temperature on mortality.

The analyses were restricted to exploring our analyses to explore the temperature–mortality association in LMA according to seasonal variation (summer and winter). The minimum mortality temperature (MMT) is the temperature at which the mortality risk is lowest; it is derived from prediction of the overall cumulative exposure–response relationship based on the best model.

The specific model was chosen on the grounds of model fit criteria, modified Akaike information criteria for models with over dispersed data, Quasi-AIC [2, 27, 52].

Table S1 presents the model formulation for 16 different models. Based on the lowest QAIC and similarly to previous studies [51], we used a quadratic B-spline was used function with 3 df to model the non-linear effects of temperature on mortality with three equidistant knots from the temperature range. We specified a natural cubic spline with three equally spaced internal knots at logarithm scale for the lag periods, 0–21 days because it is flexible to handle endpoints of data where some degree of non-linearity is expected [53].

Minimum temperature was used for winter association and maximum temperature was used for summer. Estimates of overall temperature–mortality associations, $\beta_{x,\ l}$, were reported as relative risks (RRs), cumulating the risk during the lag period.

Furthermore, the heterogeneity effects of different vulnerable subpopulations were investigated. The temperature–mortality associations were estimated separately for age groups and tested significant differences between effect estimates for two subpopulations using z-test [54, 55].

Attributable Risk from DLNMs

The attributable risk measures were derived from DLNM as indicators of the exposure-related health burdens. The attributable fraction $AF_{x,\ t}$ and number $AN_{x,\ t}$ are the percentage and number of deaths that can be attributed to temperature [52, 56]. These measures were derived via a backward perspective using the minimum incidence percentile across the entire exposure spectrum as the reference and cutoff for optimum temperature value. That is, the percentage/number of deaths that can be attributable to a series of lagged effects of temperature events in the past, up to a maximum lag of 21 days, was estimated.

Given that the risk on day t is attributable to a series of exposure events, x_t , in the past (backward perspective), the attributable fraction ($b\ AF_{x,\ t}$) and number ($b\ AN_{x,\ t}$) are described as follows:

$$
\begin{aligned}
b\text{–}AF_{x,t} &= 1\text{–}e^{-\sum_{l=l_0}^{L}\beta_{x_{t-l},l}} \\
b\text{–}AN_{x,t} &= b\text{–}AF_{x,t}\cdot n_t
\end{aligned}
\tag{2}
$$

where $\beta_{x,\ l}$ are the contributions to the risk on day t from previous exposures $x_{t-l_0}, \ldots., x_{t-21}$ experienced at $t-l_0$, ….. , $t-21$; n_t is the number of deaths on day t; b $\mathrm{AN}_{\mathrm{x},\ \mathrm{t}}$ and b $\mathrm{AF}_{\mathrm{x},\ \mathrm{t}}$ are interpreted as the number of deaths and the related fraction on day t attributable to past temperature exposures, x in the period $t-l_0$, …. . , $t-21$, compared to a constant exposure x_0 within the same period. The attributed measures were estimated for each vulnerable group separately and combined for cold and heat contributions. The contributions were further separated into moderate and cold/heat temperatures. Temperatures between the 1st percentile and MMT in the winter are classified as moderate cold, while those between MMT and the 99th percentile in the summer are classified as moderate heat. Similarly, extreme cold/heat temperatures are based on cutoff values—the 1st and 99th percentiles, corresponding to <2.9 °C and >37.3 °C, respectively.

The confidence intervals for the attributable risks were obtained by empirically reconstructing the distributions of the risk measure via Monte Carlo simulation, which produced the empirical confidence intervals (eCI) of the resulting distributions. The simulation was based on 5000 random samples with 2.5th and 97.5th percentiles of the resulting distribution interpreted as 95% eCI.

All statistical analyses and modelling were performed with R version 3.6.2 (The R Project for Statistical Computing, http://www.r-project.org) using the "DLNM" package [46].

Sensitivity Analysis

Sensitivity analysis was performed to assess whether the model parameters were robust to changing dfs (1–4) for each year to control long-term trend and varying the knot position and number for the exposure (Table S1).

Results

Summary of Mortality and Temperature Variables

Table 1 presents descriptive statistics of daily mortality counts and temperature. The maximum temperatures ranged from 15.7 to 42.0°C in summer, while daily minimum temperatures ranged from 0.1 to 17.1°C in the winter period. Over the study period, 1986–2015, there were more deaths in the winter—279,349 (mean ± SD, 19.2±7.3)—than in the summer—210,586 (mean ± SD, 14.4±5.3)—and most of these deaths were among people aged 75 years and older. The number of deaths in the winter increased from 7449 in 1986 to 10,686 in 2015, while summer deaths increased from 5684 to 7454 during the same period (Fig. 2). This implies that the number of winter deaths exceeds the number of summer deaths by 1765 to 3232 during the period under study (Fig. 2). In terms of age, a decrease in the number of deaths in the winter and summer periods from 1986 to 2015 among people aged less than 75 years was noted, but an increase was observed in the remaining age groups during the same period. The average EMWS Index over the study period was 33.61%, increasing from 18.72 to 54.68% (Fig. 2).

Temperature–Mortality Association

Figure 3 presents the three-dimensional plots of temperature–mortality associations along the 21 lag days and temperature values. In the summer months (top panel), the age-specific and all ages temperature-RR curves indicated a non-linear relationship with high RRs at high temperature and slightly delayed. The heat effects were generally more prominent at lag 2 days across all age groups. On the contrary, for the winter months (bottom panel), for all age groups, both cold and heat effects showed positive associations. However, similar to summer months, the effects were delayed for a few days (see bottom panel of Figs. 3 and 4 for lag-specific effects).

The associations displayed on Figs. 3 and 4 refer to MMT, for summer and winter months, respectively. As shown in Fig. 4 (top panel), the daily maximum summer temperature was associated with a significantly increased risk of mortality across all ages and J-shaped. The effects of summer temperatures increase significantly with age. The significantly increased risk was generally observed with lag 0–5 days and it decreases over time, except for people aged 65–74 years (Fig. 4,

Table 1 Descriptive summaries of mortality across ages and daily temperature (°C) in Lisbon Metropolitan Area (LMA), Portugal 1986–2015

Variables	Mean	Total	SD	Median	P25	P75
Mortality[‡]						
Summer						
All ages	14.4	210586	5.3	14.0	11.0	18.0
0–64 years	13.4	48987	4.1	13.0	11.0	16.0
65–74 years	12.0	44002	3.8	12.0	9.0	14.0
75–84 years	18.4	67229	5.0	18.0	15.0	21.3
85+ years	13.8	50368	5.9	13.0	10.0	17.0
Winter						
All ages	19.2	279349	7.3	18.0	14.0	24.0
0–64 years	15.4	56036	4.5	15.0	12.0	18.0
65–74 years	15.4	55927	4.4	15.0	12.0	18.0
75–84 years	25.5	92801	6.5	25.0	21.0	30.0
85+ years	20.5	74585	8.0	19.0	15.0	25.0
Daily temperature measures (°C)	**Mean**	**SD**	**Min**	**P1**	**P99**	**Max**
All year[†]	16.5	7.4	0.1	4.3	35.1	42.0
Maximum temperature	25.3	4.4	15.7	17.9	37.3	42.0
Minimum temperature	9.5	2.9	0.1	2.9	15.9	17.7

[‡] Descriptive sumaries of daily mortatility counts

[†] Based on minimum temperatures for the winter months and maximum for summer and mean temperature otherwise

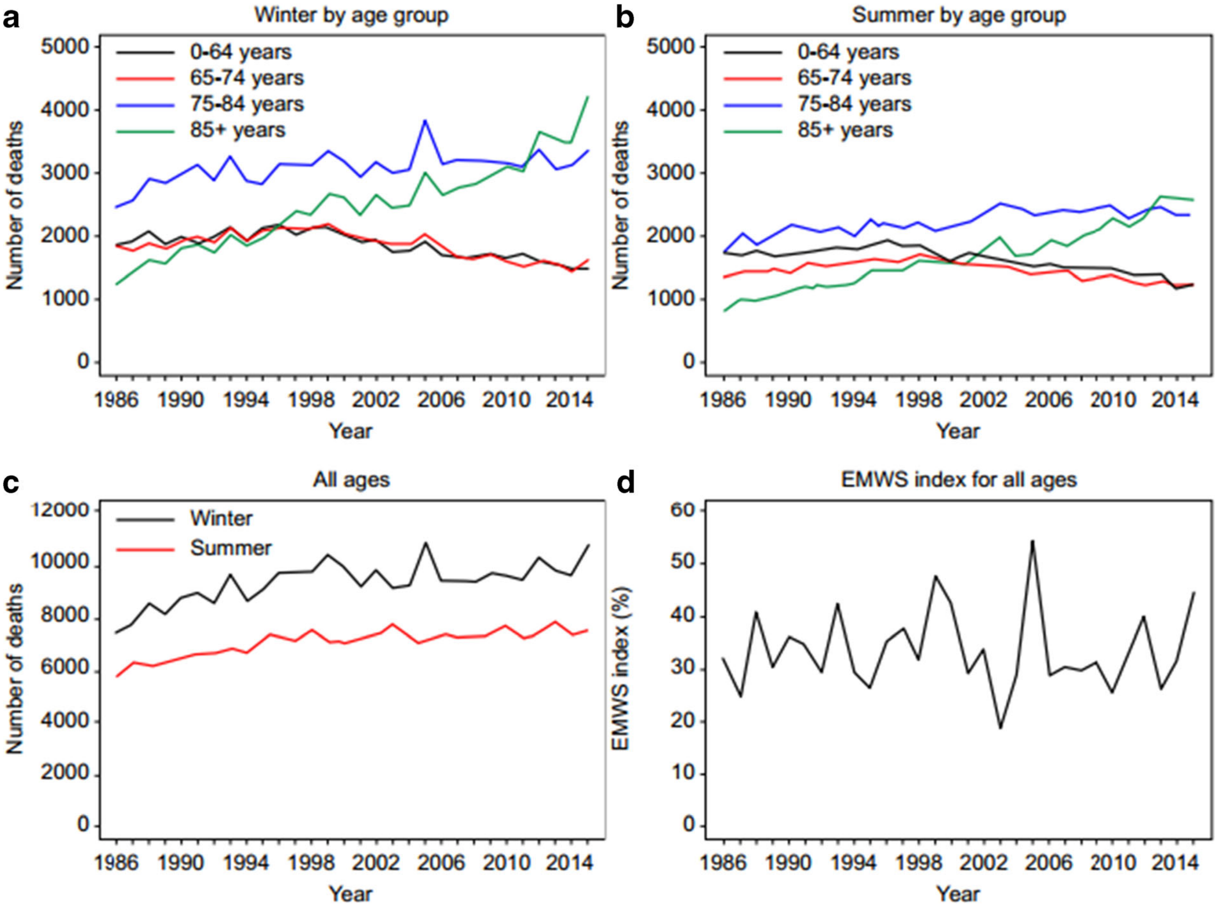

Fig. 2 Trends in the number of deaths in winter and summer in Lisbon Metropolitan Area between 1986 and 2015

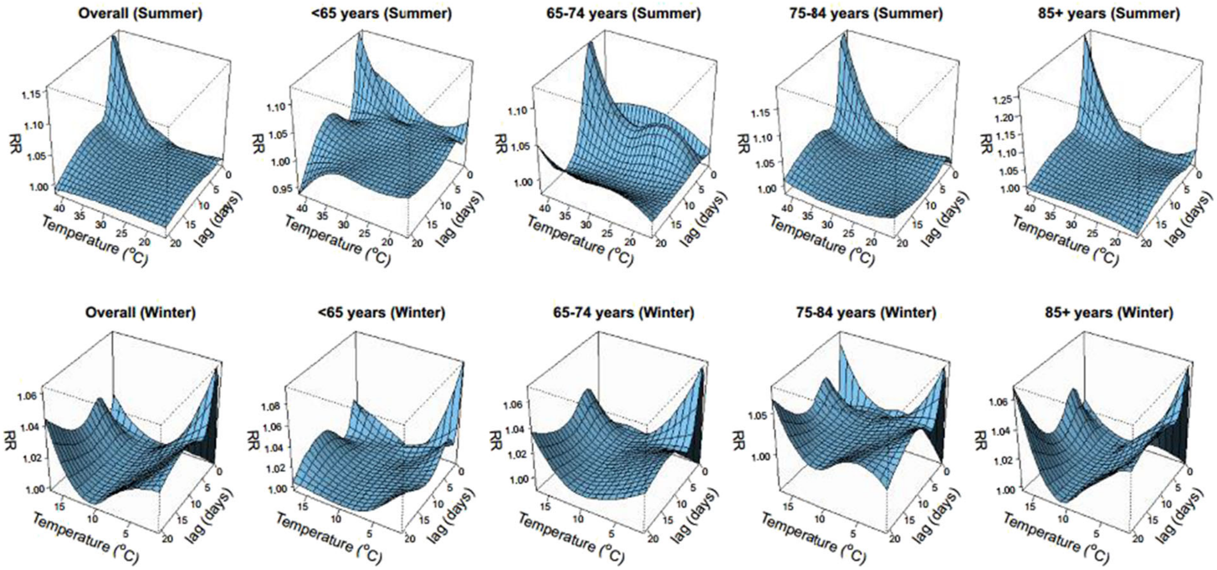

Fig. 3 3D plot of the relative risks for different ages (all ages, < 65 years, 65–74 years, 75–84 years, 85+ years) by temperature along 21 lag days in LMA, 1986–2015. Top panel: summer months; bottom panel: winter months

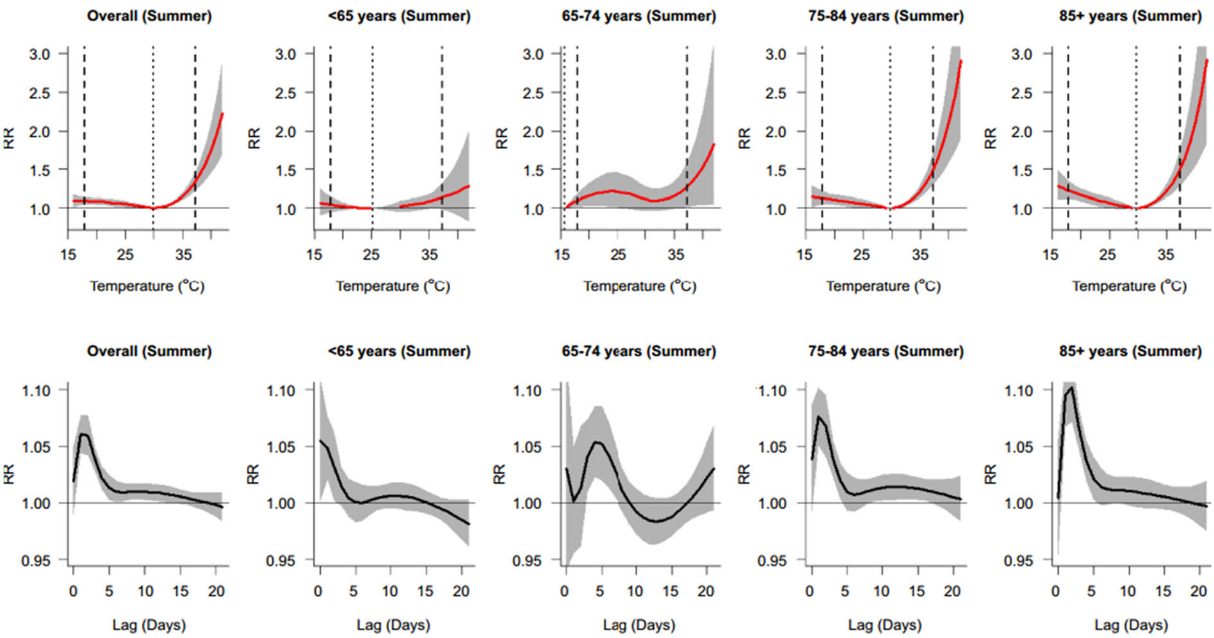

Fig. 4 (Top) Cumulative mortality risks (RR) associated with daily maximum summer temperature. The dotted line represents MMT, while the dashed lines represent the 1st and 99th percentile temperatures corresponding to 17.9 °C and 37.3 °C. (Bottom) Lag–response relationship between temperature (99th percentile, 37.3 °C) and mortality

bottom panel). For example, at a 99th summer temperature exposure of 37.3°C for all ages, the highest RR was observed at lag 2 (RR=1.06, 95% CI: 1.04–1.06), while the RR for people aged 85+ peaked at lag 2 days, with RR=1.10 (95% CI: 1.07–1.13). The overall cumulative RR (lag 0–21 days) associated with exposure to a 99th percentile summer temperature of 37.3°C was 1.3 (95% CI: 1.2–1.5) with reference to MMT of 30.0 °C (Fig. 4, top panel). Stratifying by age, the highest cumulative effect was observed among people aged 85+ years (RR=1.5, 95% CI: 1.3–1.8), and the lowest effect was observed among people aged 0–64 years (RR=1.1, 95% CI: 1.0–1.3). For all age groups, the effect of extreme heat is significantly higher among the elderly (aged 65 years and older) compared to people aged 0–64 years (Table S2).

The MMT during winter months was 9.7 °C (95% CI: 8.4–10.6 °C) for 0–64 years to 11.2 °C (95% CI: 10.6–11.4 °C) for 85+ years. The relationship between mortality and daily minimum temperature was U-shaped, implying that both extreme cold and moderate cold temperatures are significantly associated with mortality in LMA (Fig. 5, top panel). This relationship was observed across all age groups. The risk remains relatively constant after lag 5 days (Fig. 5, bottom panel). For example, for all ages, the highest RR was observed at lag 2 (RR=1.04, 95% CI: 1.01–1.06) after exposure to a 1st percentile winter temperature of 2.9 °C. Similarly, the RR for people aged 85+ years peaked at lag 2 days, with (RR=1.04, 95% CI: 1.01–1.06). In the same vein, with reference to MMT, the overall cumulative effect associated with exposure to extreme cold (1st percentile winter temperature of 2.9 °C) was 1.7 (95% CI: 1.5–1.8) for all ages. For the subgroup analyses, the cumulative effect of winter extreme temperature on mortality remained significant and lowest among people aged 0–64 years (RR=1.4, 95% CI: 1.3–1.6) and highest among people aged 85+ years (RR=2.0, 95% CI: 1.8–2.2). This effect was only significantly higher among the elderly (85+ years) compared to those younger than 65 years (Table S2).

Risk Attributable to Temperature

Tables 2 and 3 show the percentage of mortality (attributable fraction) that can be attributed to temperature for overall exposure and separately for exposure to moderate and extreme cold temperature. Similarly, attributed numbers (AN) were presented in Tables S3 and S4 for winter and summer, respectively. Generally, more deaths were attributed to winter cold temperatures than summer hot temperatures. For example, for all ages,

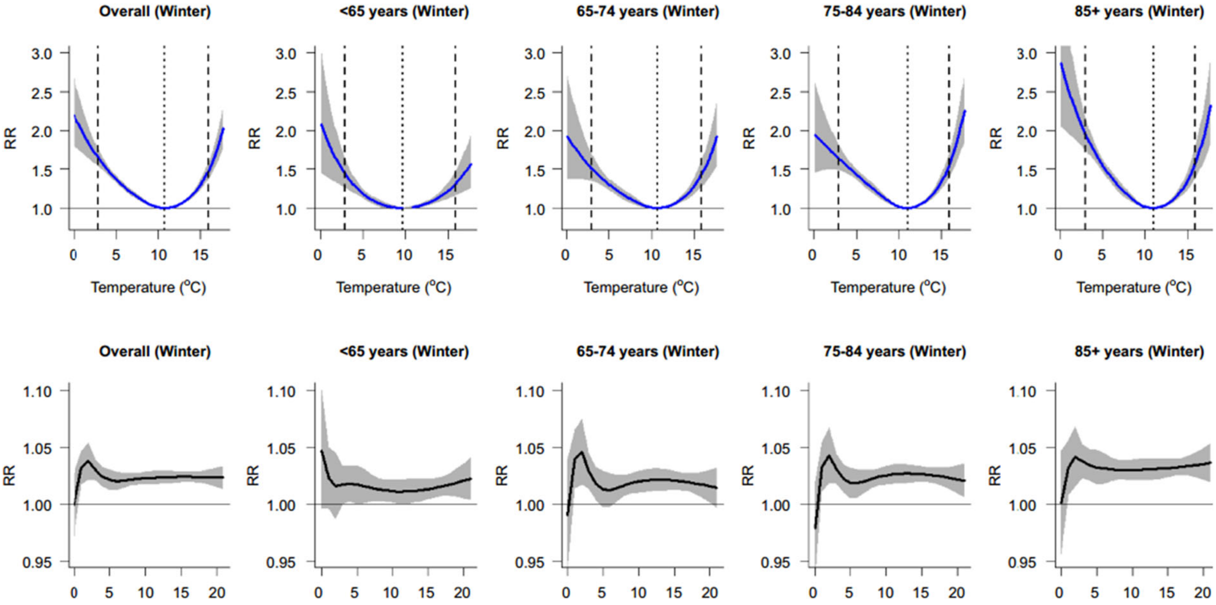

Fig. 5 (Top) Cumulative mortality risks (RR) associated with daily minimum winter temperature. The dotted line represents MMT, while the dashed lines represent the 1st and 99th percentile temperatures corresponding to 2.9 °C and 15.9 °C. (Bottom) Lag–response relationship between temperature (1st percentile, 2.9 °C) and mortality

10.7% (95% CI: 9.3–12.1%) deaths were attributed to cold temperatures in the winter and mostly due to moderate cold temperatures, 7.0% (95% CI: 6.2–7.8%), against extreme cold temperatures, 1.4% (95% CI: 0.9–1.8%). When stratified by age, people aged 85+ years were more burdened by cold temperatures (AF=13.8%, 95% CI: 11.5–16.0%).

Overall, for all ages, 5.6% of deaths (95% CI: 2.7–8.4%) can be attributed to hot temperatures. It was observed that the proportion of deaths attributed to exposure to extreme heat is higher than moderate heat. Similar to cold temperatures, people aged 85+ years are the most vulnerable age group to heat, 8.4% (95% CI: 3.9%, 2.7%), and mostly due to extreme heat, 1.3% (95% CI: 0.8–1.8%).

Sensitivity Analysis

We carried out sensitivity analyses by varying the degrees of freedom for Date (df/year) and we varied the smooth functions and knot placement for temperature (Table S1). This method was initially used to select model parameters by assessing several df and exploring several cross-basis functions for exposure–response and lag–response relationships. The temperature–mortality relationship was modelled by exploring linear and

Table 2 Total mortality fraction (%) attributable to winter temperature, reported as components from overall, moderate, and extreme cold contributions with 95% empirical confidence intervals (eCI)

Age groups	MMT	Mortality attributable fraction (%)		
		Overall	Moderate cold	Extreme cold
All ages	10.8 (10.6, 11.0)	10.7 (9.3,12.1)	7.0 (6.2, 7.8)	1.4 (0.9, 1.8)
0–64 years	9.7 (8.4, 10.6)	5.2 (2.6, 7.7)	3.2 (1.7, 4.7)	0.4 (0.3, 0.6)
65–74 years	10.7 (10.1, 11.1)	9.2 (6.9, 11.5)	5.8 (4.4, 7.1)	1.1 (0.2, 1.8)
75–84 years	11.0 (10.7, 11.3)	12.4 (10.4, 14.3)	8.0 (6.8, 9.1)	2.0 (1.3, 2.6)
85+ years	11.0 (10.6, 11.3)	13.8 (11.5, 16.0)	9.3 (8.1, 10.5)	2.0 (1.2, 2.8)

Note: Extreme cold is based on temperature (Tmin) cutoff values—the 1st percentiles corresponding to <2.9 °C—while moderate cold is based on 1st percentile and MMT in each category

Table 3 Total mortality fraction (%) attributable to summer temperature, reported as components from overall, moderate, and extreme heat contributions with 95% empirical confidence intervals (eCI)

Age groups	MMT	Mortality attributable fraction (%)		
		Overall	Moderate heat	Extreme heat
All ages	30.0 (25.6, 30.5)	5.6 (2.7, 8.4)	0.5 (0.3, 0.7)	0.9 (0.6, 1.2)
0–64 years	25.2 (15.7, 42.0)	1.6 (−0.9, 4.0)	0.2 (−0.1, 0.4)	0.9 (−0.9, 2.6)
65–74 years	15.7 (15.7, 32.2)	15 (−0.1, 27)	0.4 (0.1, 0.7)	1.4 (0.5, 2.6)
75–84 years	29.7 (26.0, 30.4)	6.7 (2.3, 10.4)	0.7 (0.4, 0.9)	1.3 (0.8, 1.7)
85+ years	29.7 (27.2, 30.5)	8.4 (3.9, 2.7)	0.7 (0.4, 0.9)	1.3 (0.8, 1.8)

Note: Extreme heat is based on cutoff values—99th percentiles corresponding to >37.3 °C—while moderate heat corresponds to temperatures (Tmax) between MMT and 99th percentiles

quadratic B-splines with 2, 3, and 4 df; the lag–mortality relationship was assessed through a natural spline with 3, 4, and 5 df; trend was captured by exploring 1–4 df per year of study. We evaluated each formulation of models (1–16) individually to identify the best combination based on the lowest QAIC. The best model (Model 8) is a quadratic B-spline function with 3 df and three equidistant knots to model temperature–mortality relationship; a natural cubic spline with three equally spaced internal knots at logarithmic scale was specified for lag–mortality, and 2 df per year for trend.

Discussion

To the best of our knowledge, this is the first long-term study to assess the effect of hot and cold temperatures on age-specific groups and attributable mortality risk by applying distributed lag non-linear models in Lisbon Metropolitan Area (LMA). Moreover, the study offers the first quantitative estimate of minimum mortality temperature (MMTs) for age groups <64 years, 65–74 years, 75–84 years, and 85+ years. This information could be used and would be needed e.g. in urban planning and implementation of adaptation action plans locally. For scientific community, this study also provides more information on varying impacts and risks of temperature extremes in a southern European country.

Southern Europe, particularly Portugal, is pointed out as one of the most vulnerable regions in Europe to the impacts of climate change and the occurrence of heat waves and cold spells, as well as frequent and intense extreme weather events [9, 57–61, 62]. Regarding human health, significant impacts directly related to extreme temperatures have been identified [12]; it should be pointed out that mortality is higher during the winter, with a greater seasonal variation in the number of deaths [63, 64]. Notably, significant impacts of hot and cold temperatures on LMA were found. In agreement with findings from several previous studies [2, 23, 65], the impacts of temperature on mortality appeared to be much higher during the cold season than the hot season: 10.7% (95% CI: 9.3–12.1%) in winter for all ages and 5.6% (95% CI: 2.7–8.4%) in summer for all ages.

Our findings emphasize the vulnerability of the elderly. In Portugal, excess winter mortality may be associated with the increased incidence of respiratory infections, mainly due to the seasonal influenza epidemic [66]. The influenza virus AH3, which sometimes circulates more widely, is quite aggressive, particularly to the elderly, given the presence of underlying chronic conditions [67, 68]. In a study conducted by Yang et al. [69], the impacts of temperature on CVD mortality appeared to be much higher during the cold season than the hot season: 35% in winter and 8% in summer. Another factor that determines population health is related to housing conditions; additionally, the conditions in the neighborhoods surrounding homes can also have major health effects [8, 19, 25, 29, 32, 69–77]. In Portugal, several population groups live in houses that have poor thermal and heating conditions [1, 78, 79], are crowded, or present poor-quality/substandard housing conditions, which have potential health consequences. Housing quality and health perception are strongly related [1, 79–83]. According to the Eurostat report [84], Portugal is the fifth country in the European Union with the largest number of people living in energy poverty, given that 19.4% of the population cannot afford to heat their homes during cold months. Among older people living alone, and with an income below the poverty threshold, 47.5% are unable to keep their homes adequately warm [78]. Older people, in particular, spend a large portion of their time indoors at home, so most of the temperatures recorded in some homes are certainly low enough to have adverse effects on health [83]. In Europe, families spend most of their energy in heating their homes [84]. Therefore, it is crucial to identify the threats, opportunities, and actions as part of coherent and integrated adaptation plans that take into account living conditions, health or personal circumstances, and information on the environment of homes and how this influence quality and well-being. This may contribute to developing and strengthening housing policies; making decisions more capable of integrating local strategies for health promotion in sectoral policies, namely in relevant strategic dimensions; and improving living conditions, mainly among population groups at risk of poverty, social exclusion, severe material deprivation, and a reduced labor intensity per capita.

Estimating temperature–mortality association for all seasons and different seasons separately is not uncommon. Several studies have already been conducted and demonstrated a monitoring of extreme cold and heat that only includes winter and summer months [63, 85]. We need an improved understanding of whether seasonal risks will change with increasing temperatures and extreme events [71, 86]in order to prepare for, alert populations to, and prevent, the major avoidable effects on health during periods of severe heat and cold, especially with regards to the most vulnerable groups. Establishing a temperature–mortality relationship is critical to the development of weather-based early warnings and the identification of vulnerable groups [33, 71, 87, 88]. According to Ebi et al. [87], the effective monitoring of vulnerability requires developing integrated programs that provide the information needed by a range of sectors, presenting useful spatial and temporal scales based on the risks that need to be managed. Our findings indicate that the mortality–temperature association in this study has different optimums for the subgroups; relative risk is the highest among the older subgroup and the lowest among the younger group. When analyzing according to subgroups, we found increased vulnerability to cold and heat among the older age groups (65–74 years, 75–84 years, and 85+ years), compared with the younger age group (< 65 years). The cumulative effect of winter and summer extreme temperatures on mortality remained significant and was highest for people aged 85+ years (RR=1.5, 95% CI: 1.3–1.8) and lowest among age group 0–64 years (RR=1.1, 95% CI: 1.0–1.3). Present results are in accordance with those of previous studies conducted in other locations. In a study conducted in Spain, the authors found a significant effect of cold on mortality for age group ≥ 65 years, while heat represented a significant risk of mortality for age group ≥ 75. In a study of 15 European cities, Analitis et al. [65] reported that the effects were clearly greater among the elderly, that temperature in the cold season is inversely associated with mortality, and that in warmer (southern) cities, the cold temperature effect is greater. Yang et al. [89] reported that the elderly, females, and individuals of lower socioeconomic status have been identified as particularly vulnerable to the effects of ambient temperatures. Scovronick et al. [90] found that the majority of the burden came from the cold, and that most of it was from moderate rather than extreme cold; in subgroup analyses, higher risks were observed among the elderly. The vulnerability of elderly age groups to ambient temperature, extreme temperature, or climate change could be explained by the prevalence of chronic and degenerative diseases, neurological and mental disorders, genitourinary morbidity, infection or inflammation of the respiratory system, high medication use, vision impairment, slow physiological adaptation, behavioral response to thermal stress, limited access to medical care, and increased dependency, such as living in nursing homes or being confined to bed [18, 19, 21, 25, 26, 38, 42, 71, 91–97]. Therefore, it is vital to prevent heat and cold-related deaths and illnesses.

Population aging is an increasing demographic process in Europe. According to the report on the impact of demographic change published by the European Commission, Portugal is the third country with the oldest population [35]. Having a low fertility rate influences this evolution, since Portugal is the country with the highest prevalence of only children in the European Union. Average life expectancy in Portugal is currently higher than 80 years old, which is above the European Union average, and the number of people aged 75 and older exceeds one million [98], which may contribute to the implosion of healthcare and social security systems, economic growth, and fiscal sustainability [34, 40, 99, 100]. In addition, the Portuguese population has a longer life expectancy, but with more comorbidities in the last years of life [98]. This and other social determinants can have potential implications for vulnerability to climate-related hazards [101], with associated implications for their management by health systems. Therefore, in order to protect population health, it is fundamental to know the resident population (its needs, health issues, habitability, etc.), assess risk factors (such as population aging, advances in the treatment of certain diseases, as well as informing people about preferred lifestyles), and assess the burden of chronic diseases to healthcare services (hospitals, health centers). The fragmentation of healthcare, namely of outpatient or primary care and hospital or secondary care, and of health sectors and social support, is a problem in most healthcare systems [102, 103]. Several European countries have been implementing programs aiming to prevent or delay chronic diseases [102]. In this sense, local and national authorities should acknowledge the importance of taking measures that allow healthcare systems to efficiently deal with, and adapt to, the challenges entailed by the prevention, treatment, and care of such diseases, according to the demographic changes in Portuguese society and considering its pronounced aging, particularly in a context of climate-related disasters. The goal is to enhance the capacity of health systems to protect and improve population health in an unstable and changing climate [104, 105]. As reported by several studies, the risks associated with extreme temperatures are more and more complex [12]. Therefore, actions aiming to protect human health should be conducted by health systems with the support of different political bodies, such as the Directorate-General of Health, seeking to realign health systems as far as prevention is concerned: from hospital administrations themselves to health centers; hospital user associations, which best describe population needs in general; agencies concerned with disaster risk management; planning authorities; as well as other government or legislative sectors concerned with financing and monetizing the proposed policies. In this context, the collaboration between different multidisciplinary teams, working closely together and following an interdisciplinary and holistic approach [106–109], is essential to the development of prevention and control programs and the implementation of planned activities.

In Portugal, even though temperature-related warnings are in place, there are limited public health intervention strategies to mitigate temperature-related deaths; these improvements, which need to be monitored and adjusted over time [30], including COVID-19 mitigation measures, should be specifically targeted at identified vulnerable populations and communities. The best practice recommends that plans be based on local epidemiologic evidence and emergency management capacity [84, 86, 107, 108]. There is an urgent need to reach a consensus as far as defining disease and temperature thresholds is concerned, regionally and locally, in order to design effective local warning systems. Inappropriate temperature indicators, thresholds, and durations could result in overestimation or underestimation of disease risk. Reinforcing monitoring systems and improving alert systems for Cold Weather and Heatwave Plans by incorporating specific definitions of temperature exposure may be conducive to effective warning systems [32, 87], which could protect more people from the adverse effects of ambient temperatures.

Some limitations should also be acknowledged. Firstly, we only considered the association between temperature and all-cause mortality, but there are other potential risk factors that were not explored in this study. Secondly, many studies have controlled for relative humidity and air pollution regarding the association between temperature and health outcomes. However, we could not control for relative humidity and air pollution in the models due to paucity of data and data unavailability for the study period. Assessing the effects of temperature and humidity separately has shown that humidity does not affect mortality [96]. Similarly, there are several highly cited studies on temperature–mortality association that do not control for humidity [1, 4, 90]. In the case of air pollution, the available literature about the confounding effect of air pollution on temperature–mortality associations shows modest [111] or no modifying effects [91]. Thirdly, different causes of death were not clearly distinguished in the aggregated all-cause data. Also, the use of exposure–lag–response relationship smooth functions is often difficult to validate in DLNM [3, 20, 112]. Finally, it is worth mentioning that although June to September was classified as summer months (and December to March as winter), extending the summer to cover April to September and winter to October–March does not show any marked differences in the temperature–mortality association. In order to reduce the effect of daily temperature variation, minimum and maximum temperatures were used in this study to explain mortality variations in winter and summer.

The differences observed in the delays between seasons in this study could be due to the cause of death. This is not surprising; a large proportion of winter deaths were said to be caused by respiratory and cardiovascular diseases [113–116] while those in the summer are usually a result of heat exhaustion and heatstroke.

Nevertheless, this study is an important addition to prior knowledge of temperature-related elderly mortality in Portugal.

Conclusions

This study examined the mortality burden attributable to ambient temperature in summer and winter in Lisbon Metropolitan, Portugal. The temperature-attributable mortality fractions were higher among the elderly, who are particularly vulnerable and have been identified as especially susceptible to temperature-associated mortality. Identifying vulnerable population subgroups and proper intervention measures at local or national level in Portugal are fundamental to health burdens associated with alert thresholds and they can be used in early warning systems and adaptation plans. Considering the 30-year time- series data used in the study, the time trend of summer– and winter–mortality burdens could have important implications for climate change adaptation.

Adopting multidisciplinary approaches and disseminating weather-related health impacts as part of the development of a thoroughly integrated health warning system could strengthen preparedness and response capacity, increasing public awareness and providing local and national measures to reduce the substantial burden of extreme temperature-related disease in Portugal, including the protection of human health and well-being.

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Declarations

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References

1. Rodrigues M, Santana P, Rocha A. Modelling climate change impacts on attributable-related deaths and demographic changes in the largest metropolitan area in Portugal: a time-series analysis. *Environ Res*. 2020;190: 109998. https://doi.org/10.1016/j.envres.2020.109998.
2. Rodrigues M, Santana P, Rocha A. Bootstrap approach to validate the performance of models for predicting mortality risk temperature in Portuguese metropolitan areas. *Environ Health*. 2019;18:25. https://doi.org/10.1186/s12940-019-0462-x.
3. Rodrigues M, Santana P, Rocha A. Effects of extreme temperatures on cerebrovascular mortality in Lisbon: a distributed lag non-linear model. *Int J Biometeorol*. 2019;63: 549–59. https://doi.org/10.1007/s00484-019-01685-2.
4. Sera F, Armstrong B, Tobias A, Vicedo-Cabrera AM, Åström C, Bell ML, Chen BY, de Sousa Zanotti Stagliorio Coelho M, Matus Correa P, Cruz JC, Dang TN, Hurtado-Diaz M, Do Van D, Forsberg B, Guo YL, Guo Y, Hashizume M, Honda Y, Iñiguez C, Jaakkola JJK, Kan H, Kim H, Lavigne E, Michelozzi P, Ortega NV, Osorio S, Pascal M, Ragettli MS, Ryti NRI, Saldiva PHN, Schwartz J, Scortichini M, Seposo X, Tong S, Zanobetti A, Gasparrini A. How urban characteristics affect vulnerability to heat and cold: a multi-country analysis. *Int J Epidemiol*. 2019;48(4): 1101–1112. https://doi.org/10.1093/ije/dyz008.
5. Meo SA, Abukhalaf AA, Alomar AA, Al-Beeshi IZ, Alhowikan A, Shafi KM, et al. Climate and COVID-19 pandemic: effect of heat and humidity on the incidence and mortality in world's top ten hottest and top ten coldest countries. *Eur Rev Med Pharmacol Sci*. 2020;24(15):8232–8.
6. Watts N, Amann M, Arnell N, Ayeb-Karlsson S, Beagley J, Belesova K, et al. The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises. *Lancet*. 2021;397(10269):129–70. https://doi.org/10.1016/S0140-6736(20)32290-X.
7. Burkart K, Meier F, Schneider A, Breitner S, Canário P, Alcoforado MJ, Scherer D, Endlicher W. Modification of heat-related mortality in an elderly urban population by vegetation (urban green) and proximity to water (urban

blue): evidence from Lisbon. *Portugal Environ Health Perspect*. 2016;124(7):927–934.

8. Howe PD, Marlon J, Wang X, Leiserowitz A. Public perceptions of the health risks of extreme heat across US states, counties, and neighborhoods. *Proc Natl Acad Sci U S A*. 2019;116(14):6743–8. https://doi.org/10.1073/pnas.1813145116.
9. Hoegh-Guldberg O, Jacob D, Taylor M, et al. Impacts of 1.5°C global warming on natural and human systems. In: Masson-Delmotte V Zhai P örtner H-O Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, UK 2018.
10. Chen R, Yin P, Wang L, Liu C, Niu Y, Wang W, et al. Association between ambient temperature and mortality risk and burden: time series study in 272 main Chinese cities. *BMJ*. 2018;363:k4306.
11. Armstrong B, Bell ML, Leon YG, et al. Longer-term impact of high and low temperature on mortality: an international study to clarify length of mortality displacement. *Environ Health Perspect*. 2017;125:107009.
12. Basu R, Malig B. High ambient temperature and mortality in California: exploring the roles of age, disease, and mortality displacement. *Environ Res*. 2011;111(8):1286–92. https://doi.org/10.1016/j.envres.2011.09.006.
13. Mora C, Dousset B, Caldwell I, et al. Global risk of deadly heat. *Nat Clim Change*. 2017;7:501–6. https://doi.org/10.1038/nclimate3322.
14. Bobb JF, Peng RD, Bell ML, Dominici F. Heat-related mortality and adaptation to heat in the United States. *Environ Health Perspect*. 2014;122(8):811–6. https://doi.org/10.1289/ehp.1307392.
15. Cardona OD, van Aalst MK, Birkmann J, Fordham M, McGregor G, Perez R, et al. Determinants of risk: exposure and vulnerability. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM, editors. A special report of working groups I and II of the Intergovernmental Panel on Climate Change (IPCC) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge: Cambridge University Press; 2012. p. 65–108.
16. Li T, Horton RM, Bader DA, Zhou M, Liang X, Ban J, et al. Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China. *Sci Rep*. 2016;6:28161. https://doi.org/10.1038/srep28161.
17. Todd N, Valleron AJ. Space–time covariation of mortality with temperature: a systematic study of deaths in France, 1968–2009. *Environ Health Perspect*. 2015;123:659–64.
18. Cutter S, Osman-Elasha B, Campbell J, Cheong SM, McCormick S, Pulwarty R, et al. Managing the risks from climate extremes at the local level. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM, editors. A special report of working groups I and II of the Intergovernmental Panel on Climate Change (IPCC) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge: Cambridge University Press; 2012. p. 291–338.
19. Rodrigues M, Santana P, Rocha A. Statistical modelling of temperature-attributable deaths in Portuguese metropolitan areas under climate change: who is at risk? *Atmosphere*. 2020;11(2):159. https://doi.org/10.3390/atmos11020159.
20. Rosenzweig C, Solecki W, Romero-Lankao P, Mehrotra S, Dhakal S, Ali Ibrahim S, editors. *Climate change and cities: second assessment report of the urban climate change research network*. Cambridge: Cambridge University Press; 2018; 811 pp. https://doi.org/10.1017/9781316563878.
21. Kenny GP, Yardley J, Brown C, Sigal RJ, Jay O. Heat stress in older individuals and patients with common chronic diseases. *CMAJ*. 2010;182:1053–60.
22. Pascal M, Wagner V, Corso M, Laaidi K, Ung A, Beaudeau P. Heat and cold related-mortality in 18 French cities. *Environ Int*. 2018;121:189–198.
23. Rodrigues M, Santana P, Rocha A. Projections of temperature-attributable deaths in Portuguese metropolitan areas: a time-series modelling approach. *Atmosphere*. 2019;10:735. https://doi.org/10.3390/atmos10120735.
24. Intergovernmental Panel on Climate Change (IPCC). In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors. *Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press; 2014. 1132 pp.
25. Marmot Review Team. The health impacts of cold homes and fuel poverty. *BMJ*. 2011;342:d2807. https://doi.org/10.1136/bmj.d2807.
26. World Health Organization (WHO). *WHO guidance for climate-resilient and environmentally sustainable health care facilities*. Geneva: World Health Organization; 2020. Licence: CC BY-NC-SA 3.0 IGO
27. Rodrigues M, Natário I, MRO Martins. Estimate the effects of environmental determining factors on childhood asthma hospital admissions in Lisbon, Portugal: a time series modelling study. *Theor Appl Climatol*. 2021;143(1):809–21. https://doi.org/10.1007/s00704-020-03415-w.
28. Rechel B, et al. Ageing in the European Union. *The Lancet*. 2013;381:1323–31.
29. Gronlund CJ, Berrocal VJ, White-Newsome JL, Conlon KC, O'Neill MS. Vulnerability to extreme heat by socio-demographic characteristics and area green space among the elderly in Michigan, 1990–2007. *Environ Res*. 2015;136:449–61.
30. Haines A, Ebi K. The imperative for climate action to protect health. *N Engl J Med*. 2019;380:263–73.
31. Ballester J, Robine JM, Herrmann FR, Rodó X. Long-term projections and acclimatization scenarios of temperature-related mortality in Europe. *Nature Commun*. 2011;2:358. https://doi.org/10.1038/ncomms1360.
32. Benmarhnia T, Bailey Z, Kaiser D, Auger N, King N, Kaufman JS. A difference-in-differences approach to assess the effect of a heat action plan on heat-related mortality, and differences in effectiveness according to sex, age, and

socioeconomic status (Montreal, Quebec). *Environ Health Perspect*. 2016;124:1694–1699.

33. Matthies F, Bickler Graham M, Neus C, Hales S. World Health Organization. Regional Office for Europe. et al., 2008. *Heat-health action plans*: guidance / edited by Franziska Matthies ... [et al.]. Copenhagen: WHO Regional Office for Europe.
34. Lutz W. (Ed.), Amran, G., Bélanger, A., Conte, A., Gailey, N., Ghio, D., Grapsa, E., Jensen, K., Loichinger, E., Marois, G., Muttarak, R., Potančoková, M., Sabourin, P., Stonawski, M., 2019. *Demographic scenarios for the EU - migration, population and education*, EUR 29739 EN, Publications Office, Luxembourg. https://doi.org/10.2760/590301,
35. European Commission, 2020. *European Commission Report on the Impact of Demographic Change*. https://ec.europa.eu/info/sites/info/files/demography_report_2020_n.pdf. Accessed 18 Sept 2020.
36. United Nations, Department of Economic and Social Affairs, Population Division, 2019. World Population Prospects 2019: highlights (ST/ESA/SER.A/423). https://population.un.org/wpp/. Accessed 14 Jul 2020.
37. European Environment Agency (EEA). *Drivers of change of relevance for Europe's environment and sustainability*. Luxembourg: Publications Office of the European Union; 2020. https://doi.org/10.2800/129404.
38. Bunker A, Wildenhain J, Vandenbergh A, Henschke N, Rocklöv J, Hajat S, et al. Effects of air temperature on climate-sensitive mortality and morbidity outcomes in the elderly; a systematic review and meta-analysis of epidemiological evidence. *EBioMedicine*. 2016;6:258–68.
39. OECD, 2019. *Health at a Glance 2019: OECD Indicators*, OECD Publishing, Paris. https://doi.org/10.1787/4dd50c09-en.
40. OECD. Pensions at a Glance 2019: OECD and G20 Indicators, OECD Publishing, Paris. https://doi.org/10.1787/b6d3dcfc-en.
41. INE – Portuguese National Statistics Institute, Statistics Portugal. https://ine.pt/. Accessed 16 Oct 2019.
42. Prince MJ, Wu F, Guo Y. et al. *The burden of disease in older people and implications for health policy and practice*. Lancet. 2015; 385:549–562.
43. World Health Organization (WHO) .*World report on ageing and health*. World Health Organization. 2015. https://apps.who.int/iris/handle/10665/186463. Accessed 14 May 2020.
44. Chau PH, Woo J. The trends in excess mortality in Winter vs. Summer in a sub-tropical city and its association with extreme climate conditions. Plos One. 2015; 10(5): e0126774. https://doi.org/10.1371/journal.pone.0126774
45. Ou CQ, Song YF, Yang J, Chau PYK, Yang L, Chen PY. *Excess winter mortality and cold temperatures in a subtropical city*, Guangzhou, China. PloS One. 2013;8(10): e77150. https://doi.org/10.1371/journal.pone.0077150.
46. Gasparrini A, Armstrong B, Kenward M. *Distributed lag non-linear models*. Stat. Med. 2010;2224–2234.
47. Wang Z, Zhou Y, Zhang Y, Huang X, Duan X, Ou Y et al. *Association of hospital admission for bronchiectasis with air pollution*: A province-wide time-series study in southern China. International Journal of Hygiene and Environmental Health. 2020;231, 113654. https://doi.org/10.1016/j.ijheh.2020.113654.
48. Gasparrini A. *Modelling exposure–lag–response associations with distributed lag non-linear models*. Statistics in Medicine. 2014;33:881–899.
49. Petkova EP, Gasparrini A, Kinney PL. *Heat and mortality in New York City since the beginning of the 20th century*. Epidemiology (Cambridge, Mass.). 2014;25:554.
50. Gasparrini A, Guo Y, Hashizume M, Kinney PL, Petkova EP, et al. *Temporal variation in heat–mortality associations: a multicountry study*. Environ Health Perspect. 2015;123(11):1200–7.
51. Guo Y, Barnett AG, Tong S. *High temperatures-related elderly mortality varied greatly from year to year: important information for heat-warning systems*. Scientific Reports. 2012;2:830.
52. Gasparrini A, Leone M. *Attributable risk from distributed lag models. BMC Medical Research Methodology*. 2014;14: 55–55.
53. Goldberg MS, Gasparrini A, Armstrong B, Valois MF. *The short-term influence of temperature on daily mortality in the temperature climate of Montreal, Canada*. Environmental Research. 2011;111(6):853–860.
54. Altman DG, Bland JM. *Interaction revisited: the difference between two estimates*. Bmj. 2003;326:219.
55. Yang J, Yin P, Sun J, Wang B, Zhou M, Li M, et al. *Heatwave and mortality in 31 major chinese cities: Definition, vulnerability and implications*. Science of The Total Environment. 2019; 649:695–702.
56. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, Tobias A, Tong S, Rocklöv J, Forsberg B, Leone M, de Sario M, Bell ML, Guo YLL, Wu CF, Kan H, Yi SM. et al. *Mortality risk attributable to and low ambient temperature: a multicountry observational study*. Lancet. 2015; 386(9991):369–375.
57. Jacob, D. et al. *Climate Impacts in Europe Under +1.5°C Global Warming*. Earth's Future.2018;6(2):264–285.
58. Forzieri G, Feyen L, Russo S, Vousdoukas M, et al. *Multi-hazard assessment in Europe under climate change*. Climatic Change. 2016;137:105–119. https://doi.org/10.1007/s10584-016-1661-x.
59. Naumann G, Russo S, Formetta G., Ibarreta D, Forzieri G, Girardello M, Feyen L. *Global warming and human impacts of heat and cold extremes in the EU*, EUR 29959 EN, Publications Office of the European Union, Luxembourg. 2020. https://doi.org/10.2760/47878,JRC118540.
60. Rocha A, Pereira SC, Viceto C, Silva R, Neto J, Marta-Almeida M. *A Consistent Methodology to Evaluate Temperature and Heat Wave Future Projections for Cities*: A Case Study for Lisbon. Applied Sciences. 2020;10(3): 1149.
61. Seneviratne, S.I., J. Rogelj, R. Séférian, R. Wartenburger, M.R. Allen, M. Cain, R.J. Millar, K.L. Ebi, N. Ellis, O. Hoegh-Guldberg, A.J. Payne, C.-F. Schleussner, P. Tschakert, R.F. Warren. *The many possible climates from the Paris Agreement's aim of 1.5∘C warming*. Nature. 2018;558, 41–49.
62. Intergovernmental Panel on Climate Change (IPCC), 2013. Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)].

2013. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp. http://www.ipcc.ch/report/ar5/2.

63. Eurowinter Group. *Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe*. Lancet. 1997; 349:1341–1346.
64. Fowler T, Southgate RJ, Waite T, Harrell R, Kovats S, Bone A, Doyle Y, Murray V. *Excess winter deaths in Europe: A multi-country descriptive analysis*. Eur J Pub Health. 2015; 25:339–345.
65. Analitis A, Katsouyanni K, Biggeri A, Baccini M, Forsberg B, Bisanti L, Kirchmayer U, Ballester F, Cadum E, Goodman PG, et al. *Effects of cold weather on mortality: results from 15 European cities within the PHEWE project*. Am J Epidemiol. 2008;168(12):1397–1408.
66. Nielsen J, Vestergaard LS, Richter L, et al. *European all-cause excess and influenza-attributable mortality in the 2017/18 season*: should the burden of influenza B be reconsidered? Clin Microbiol Infect. 2019;25(10):1266–1276.
67. Loubet P, Samih-Lenzi N, Galtier F, Vanhems P. et al. *Factors associated with poor outcomes among adults hospitalized for influenza in France*: a three-year prospective multicenter study. J Clin Virol. 2016;79:68–73.
68. Mosnier A, et al. *Does seasonal vaccination affect the clinical presentation of influenza among the elderly?* A cross-sectional analysis in the outpatient setting in France. 2003–2014. Vaccine. 2017;35:2076–2083.
69. Yang J, Zhou M, Ou CQ, Yin P, Li M, Tong S, Gasparrini A. *Seasonal variations of temperature-related mortality burden from cardiovascular disease and myocardial infarction in China*. Environ. Pollut. 2017;224: 400–406.
70. Ige J, Pilkington P, Orme J. *The relationship between buildings and health*: a systematic review. J Public Health. 2019;41(2):e121–e132.
71. Hajat S, Chalabi Z, Wilkinson P, Erens B, Jones L, Mays N. *Public health vulnerability to wintertime weather: time-series regression and episode analyses of national mortality and morbidity databases to inform the Cold Weather Plan for England*. Public Health. 2016; 137:26–34.
72. Diez-Roux AV. Neighborhoods and health: Where are we and were do we go from here? Environnement résidentiel et santé: État de la question et perspectives pour le futur. Revue D'epidemiologie et de Sante Publique. 2007; 55:13–21. https://doi.org/10.1016/j.respe.2006.12.003.
73. IPCC, Intergovernmental Panel on Climate Change. Summary for Policymakers. In: Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland; 2018. 32 pp.
74. Marmot, M., 2010. *Fair society, healthy lives: The Marmot Review*. Strategic review of health inequalities in England post-2010. 2015. London: The Marmot Review.
75. Rojas-Rueda D, Nieuwenhuijsen MJ, Gascon M, Perez-Leon D, Mudu P. *Green spaces and mortality: a systematic review and meta-analysis of cohort studies*. Lancet Planetary Health. 2019;3(11):E469-E477. https://doi.org/10.1016/S2542-5196(19)30215-3.
76. World Health Organization (WHO). *Housing and health guidelines*. Geneva: World Health Organization. Licence: CC BY-NC-SA 3.0 IGO. 2018.
77. Rodgers SE, Bailey R, Johnson R, Poortinga W, Smith R, Berridge D. *Health impact, and economic value, of meeting housing quality standards*: a retrospective longitudinal data linkage study. Public Health Res. 2018;6(8). https://doi.org/10.3310/phr06080. Accessed 20 Jan 2020.
78. Eurostat, 2019. *Can you afford to heat your home?*. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200106-1?inheritRedirect=true&redirect=%2Feurostat%2Fhome. Accessed 02 Mar 2020.
79. Eurostat. Living conditions in Europe - 2018 edition, Cat. No KS-DZ-18-001-EN-N. https://doi.org/10.2785/39876.
80. CSDH, Commission on Social Determinants of Health.Closing the gap in a generation: health equity through action on the social determinants of health. *Final Report of the Commission on Social Determinants of Health*. Geneva, World Health Organization. 2008. https://apps.who.int/iris/handle/10665/43943. Accessed 02 Mar 2020
81. Thomson H, Thomas S, Sellstrom E, Petticrew M. *Housing improvements for health and associated socio-economic outcomes*. Cochrane Database Syst Rev. 2013;2:CD008657.
82. Murage P, Kovats S, Sarran C, Taylor J, McInness R, Hajat S. What individual and neighbourhood-level factors increase the risk of heat-related mortality? A case-crossover study of over 185,000 deaths in London using high-resolution climate datasets. *Environment International*. 2019;134: 105292.
83. Wilkinson P, Landon M, Armstrong B, Stevenson S, McKee M. *Cold comfort: the social and environmental determinants of excess winter death in England*, 1986-1996. York: Joseph Rowntree Foundation. 2001.
84. Eurostat. Energy consumption and use by households. 2020. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200626-1?inheritRedirect=true&redirect=%2Feurostat%2F. Accessed 28 June 2020.
85. Robine JM, Michel JP, Herrmann FR. *Excess male mortality and age-specific mortality trajectories under different mortality conditions*: a lesson from the heat wave of summer 2003. Mech. Ageing Dev. 2012;133:378–386.
86. Hess JJ, Ebi KL. *Interative management of heat early warning systems in a changing climate*. Ann. N. Y. Acad. Sci.2016;1382: 21–30.
87. Ebi KL, Boyer C, Bowen KJ, Frumkin H, Hess J. *Monitoring and Evaluation Indicators for Climate Change-Related Health Impacts*, Risks, Adaptation, and Resilience. Int J Environ Res Public Health. 2018;15:1943.
88. Berry P, Enright PM, Shumake-Guillemot J, Villalobos Prats E, Campbell-Lendrum D. *Assessing health vulnerabilities and adaptation to climate change*: A review of

international progress. Int J Environ Res Public Health. 2018;15(12):2626.

89. Yang J, Ou C, Ding Y et al. *Daily temperature and mortality: a study of distributed lag non-linear effect and effect modification in Guangzhou*. Environ Health. 2012;11:63.

90. Scovronick N, Sera F, Acquaotta F, Garzena D, Fratianni S, Wright CY, Gasparrini A. *The association between ambient temperature and mortality in South Africa*: A time-series analysis. Environ Res. 2018;161:229–235.

91. Rocklöv J, Forsberg B, Meister K. *Winter mortality modifies the heat-mortality association the following summer*. Eur Respir J. 2009;33: 245–251.

92. Mølbak K, Espenhain L, Nielsen J, Tersago K, Bossuyt N, Denissov G. et al. *Excess mortality among the elderly in European countries*, December 2014 to February 2015. Euro Surveill. 2015;20:21065.

93. Nunes AR. *Determinants of general and specified resilience to extreme temperatures*. Weather, Climate and Society. 2020;12(4):913–928.

94. Campbell-Lendrum D, Corvalán C. *Climate Change and Developing-Country Cities*: Implications For Environmental Health and Equity. J Urban Health. 2007;84:109–117.

95. Ballester J, Rodo X, Robine JM, Herrmann FR. *European seasonal mortality and influenza incidence due to winter temperature*. Nature Clim Change.2016;6(10): 927–30.

96. Petkova EP, Dimitrova LK, Sera F, Gasparrini A. *Mortality attributable to heat and cold among the elderly in Sofia, Bulgaria*. Int J Biometeorol. 2021. https://doi.org/10.1007/s00484-020-02064-y.

97. Lim YH, Reid CE, Honda Y, Kim H. *Temperature deviation index and elderly mortality in Japan*. Int J Biometeorol. 2016;60:991–8.

98. Ministério da Saúde, 2018. *Retrato da Saúde*, Portugal.

99. European Environment Agency (EEA). *The sustainability transition in Europe in an age of demographic and technological change. An exploration of implications for fiscal and financial strategies*. Luxembourg: Publications Office of the European Union; 2020. https://doi.org/10.2800/571570.

100. Simões J, Augusto G, Fronteira I, Hernandez-Quevedo C. Portugal: health system review. *Health Systems in Transition.* 2017;19(2):1–184.

101. Tong S, Ebi K. *Preventing and mitigating health risks of climate change*. Environ Res. 2019;174:9–13.

102. Gaal P. et al. Hungary. In: Nolte E, Knai C, eds. *Assessing chronic disease management in European health systems*. Country reports. Copenhagen, WHO Regional Office for Europe on behalf of the European Observatory on Health Systems and Policies. 2015.

103. Nolte, E., Knai, C., McKee, M. (eds.). *Managing chronic conditions: experience in eight countries*. Copenhagen, World Health Organization on behalf of theEuropean Observatory on Health Systems and Policies. 2008.

104. De'Donato F, Scortichini M, De Sario M, de Martino A, Michelozzi P. *Temporal variation in the effect of heat and the role of the Italian heat prevention plan*. Public Health. 2018;161:154–162.

105. World Health Organization (WHO). *Operational framework for building climate resilient health systems*. Geneva: United Nations. This guidance document outlines the components of a climate resilient health system and the approaches and tools available to promote resilience. 2015.

106. Ebi KL, Berry P, Hayes K, Boyer C, Sellers S, Enright PM, Hess JJ. *Stress Testing the Capacity of Health Systems to Manage Climate Change-Related Shocks and Stresses*. Int. J. Environ. Res. Public Health. 2018; 15, 2370.

107. Conlon K, Monaghan A, Hayden M, Wilhelmi O. *Potential Impacts of Future Warming and Land Use Changes on Intra-Urban Heat Exposure in Houston, Texas*. PLoS ONE. 2016. 11(2):e0148890. https://doi.org/10.1371/journal.pone.0148890.

108. McGregor GR, Bessemoulin P, Ebi K, Menne B. Heatwaves and Health: *Guidance on Warning-System Development*; World Meteorological Organization and World Health Organization: Geneva, Switzerland. 2015;1–114.

109. Ebi KL, Hess JJ, Isaksen TB, et al. *Using Uncertain Climate and Development Information in Health Adaptation Planning*. Curr Environ Health Rep. 2016; 3(1):99–105.

110. Åström C, Åström DO, Andersson C, Ebi KL, Forsberg B. *Vulnerability Reduction Needed to Maintain Current Burdens of Heat-Related Mortality in a Changing Climate—Magnitude and Determinants*. International Journal of Environmental Research and Public Health. 2017;14(7):741.

111. Brooke AG, Bell ML. *Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States*. Epidemiology. 2009;20:205–213.

112. Gasparrini A. et al. *Projections of temperature-related excess mortality under climate change scenarios*. The Lancet Planetary Health. 2017;e360–e367

113. Keatinge WR. *Winter mortality and its causes*. International Journal of Circumpolar Health. 2002;61: 292–299.

114. Chen K, Breitner S, Wolf K, Hampel R, Meisinger C, Heier M, von Scheidt W, Kuch B, Peters A, Schneider A, Group KS. *Temporal variations in the triggering of myocardial infarction by air 15 temperature in Augsburg*, Germany, 1987-2014. Eur Heart J. 2019;40(20):1600–1608.

115. Zanobetti A, O'Neill MS, Gronlund CJ, Schwartz JD. *Summer temperature variability and long-term survival among elderly people with chronic disease*. Proc Natl Acad Sci U S A. 2012;109(17):6608–13.

116. Guo H, Chen P, Long S, Su H. *Effects of extreme cold weather on the mortality of cardiovascular and respiratory diseases in Taiwan*. Epidemiology. 2007;18(5):S70.