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Statistical Modelling of Temperature-Attributable Deaths in Portuguese Metropolitan Areas under Climate Change: Who Is at Risk?

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Abstract: Several studies emphasize that temperature-related mortality can be expected to have differential effects on different subpopulations, particularly in the context of climate change. This study aims to evaluate and quantify the future temperature-attributable mortality due to circulatory system diseases by age groups (under 65 and 65+ years), in Lisbon metropolitan area (LMA) and Porto metropolitan area (PMA), over the 2051–2065 and 2085–2099 time horizons, considering the greenhouse gas emissions scenario RCP8.5, in relation to a historical period (1991–2005). We found a decrease in extreme cold-related deaths of 0.55% and 0.45% in LMA, for 2051–2065 and 2085–2099, respectively. In PMA, there was a decrease in cold-related deaths of 0.31% and 0.49% for 2051–2065 and 2085–2099, respectively, compared to 1991–2005. In LMA, the burden of extreme heat-related mortality in age group 65+ years is slightly higher than in age group <65 years, at 2.22% vs. 1.38%, for 2085–2099. In PMA, only people aged 65+ years showed significant temperature-related burden of deaths that can be attributable to hot temperatures. The heat-related excess deaths increased from 0.23% for 2051–2065 to 1.37% for 2085–2099, compared to the historical period.

Keywords: climate change; extreme temperatures; distributed lag non-linear model (DLNM); mortality; elderly; projections; WRF model; Portugal

1. Introduction

The association between extreme temperatures and mortality in urban areas has been identified in previous studies [1–11]. Additionally, studies from Portugal report that a large proportion of such excess mortality in the hot season is caused by cardiovascular diseases, cerebrovascular diseases, and diseases of the respiratory system. This mortality is higher among the elderly and people with pre-existing conditions [1,12,13]. Concerning the cold season, Portugal has been mentioned over the years as having one of the highest rates of excess winter mortality in Europe [14–17], which may be related to socioeconomic conditions and population health status. Most often, this excess has been attributed to the influenza virus, mainly among the most vulnerable populations, due to the spread of respiratory infections and the decompensation caused by chronic illnesses [1,9,18–20].

Though many studies demonstrate the association between extreme temperatures and mortality, the Intergovernmental Panel on Climate Change (IPCC) Assessment Report [21] IPCC, and the World Health Organization [22] consider that research on the impacts of climate change, such as temperature-related mortality [23], should be intensified so as to characterize and identify the most vulnerable population groups, taking urban context into account [24]. Urban areas are particularly vulnerable to the effects of extreme temperatures [25] due to the high concentration of the susceptible population (elderly, impoverished populations, people with chronic health conditions, including diabetes, people using certain medications, the mentally ill and outdoor workers) [26,27], buildings, number of green areas or vegetative covering [28,29] and the nature of infrastructures [30,31].

In a context characterized by climate change, future scenario-based projections have stood as the main approach when it comes to planning and formulating policies. Climate change is expected to bring about a temperature increase between 1.6 °C and 4.5 °C by 2100 [32]. More importantly, temperature extremes have become more frequent and intense, and this trend is expected to continue in the future [33–35]. These projections have been estimated for many regions [36–38], and particularly for Europe [39,40], the Mediterranean [41–43], and the Iberian Peninsula [44]. Heat waves are such type of temperature extreme events that may bring continuous thermal stress for periods of days and are associated to increased mortality [45,46]. The frequency and intensity of heat waves is also expected to increase in the future in many regions [47–49]. This has been reported for Europe [50–54] and particularly for the Iberian Peninsula [55,56]. Pereira et al. [55] estimated projections of heat waves for 12 cities in the Iberian Peninsula for the Representative Concentration Pathway 8.5 (RCP8.5) greenhouse gas emission scenario. They report very large increases in the average number of heat wave days per year, up to 10-fold in some cities which may experience heat wave conditions during most of the summer by 2100.

Accordingly, the aim of this study is to quantify attributable mortality while identifying and characterizing the age groups (aged less than 65 and 65+ years) that are more vulnerable to the health impacts of climate change in Portuguese metropolitan areas (Lisbon and Porto), over the 2046–2065 and 2080–2099 time horizons, under a Representative Concentration Pathway 8.5 (RCP8.5) greenhouse gas emission scenario.

2. Data and Methods

2.1. Mortality Data

For this study, we first collected daily deaths due to diseases of the circulatory system from metropolitan areas (LMA, Lisbon metropolitan area; PMA, Porto metropolitan area). Data on the daily counts of deaths from 1 January 1 1991 to 31 December 2005 were collected from the Statistics Portugal. Mortality data were classified into the following categories using the International Classification of Diseases, Ninth Revision (ICD-9) and the International Statistical Classification of Diseases and Related Health Problems, Tenth Revision (ICD-10): Diseases of the Circulatory System (ICD–9: 390-459, ICD-10: I00-I99). To account for population aging, mortality data were disaggregated by two age groups (0–65 years and 65+ years).

2.2. Temperature Projections

In this study, the simulations were performed using the Weather Research and Forecast–Advanced Research weather (WRF) model v3.5 [57] to dynamically downscale climate simulations from the Max Planck Institute Earth System Model (MPI-ESM-LR) [58], for time periods namely, a recent past climate (1991–2005), a mid-term future climate (2051–2065) and a long-term future climate (2085–2099). The simulations were performed using the RCP8.5 emission scenario [59,60]. The RCP8.5 scenario represents relatively high greenhouse gas emissions, with a radiative forcing reaching 8.5 $W.m^2$ by 2100 [21,61], as detailed in the fifth IPCC report [61]. Systematic biases in daily temperatures were removed by applying the quantile-based mapping bias correction method [62]. This method has already shown to be adequate to be suitable to produce bias corrected high-resolution meteorological information for climate change impact studies [55,63,64]. As reported by Dosio et al. [65], bias correction of climate simulations is deemed necessary for climate impact studies because climate model outputs may present bias when compared with observed data [66]. Previously, the present data were submitted to bias correction to minimize model systematic errors to relative observations [9,55].

2.3. Statistical Approach

2.3.1. Estimation of Temperature-Mortality Association

In this study, mean daily temperature was used to examine the current temperature-mortality association in Porto and Lisbon metropolitan areas. We used distributed lag non-linear models (DLNMs) [1,9,67–70] assuming a quasi-Poisson distribution. We simultaneously explored the non-linear and delayed effects of temperature, adjusted for long-term temporal trends, day of the week (DOW), and holiday (Hoy).

The model is formulated as follows:

$$\log[E(Y_{it})] = Yt \sim quasiPoisson(\mu t) \tag{1}$$

$$\log(\mu t) = \alpha + offset\ (Population) + cb(Tmean) + ns(time,\ df = n, year) + \gamma DOW + \lambda Hoy$$

The daily number of deaths on day t is represented by Yt; α is the intercept; ns is the natural cubic spline to capture long-term trend and seasonality with 3 degrees of freedom per year of study; $cb(Tmean)$ was used to model the non-linear and delayed effect of temperature through a bi-dimensional cross-basis function, described by a natural cubic spline with 4 degrees of freedom (dfs) for the exposure-response association, with four internal knots placed at equal intervals in the temperature range and the log scale of lags without intercept. The maximum lag was set at 30 days [1,9,20]. We accounted for linear effects binary indicator of day of the week (DOW) and holiday (Hoy), where γ and λ represent vector of coefficients of DOW and Hoy, respectively.

Furthermore, we assessed whether the associations varied by seasons (summer: June–September; and winter: December–March) [9] and age group (0–65 years and 65+ years). The heat effects were assessed using the data restricted to the summer months, and extreme hot was defined as the 99th percentile of the mean temperature. Similarly, data restricted to winter months was used to assess the cold effects with extreme cold classified as the first percentile of the mean temperature. Minimum mortality temperatures (MMT) were set as threshold temperatures for hot and cold.

For the model, the exposure-response curves for temperature-mortality associations were presented as log relative risk (logRR) of death for every unit increase/decrease in temperature with reference to the minimum mortality threshold/temperature (MMT). Minimum mortality temperature (MMT) is the temperature at which the mortality risk is at its lowest, and is derived from the prediction of the overall cumulative exposure-response relationship, based on the above-described model. The derivation of MMT is a straightforward scan through the temperature-mortality function to find the temperature value that minimizes the function [71].

2.3.2. Attributable Risk from DLNMs

Estimated temperature-mortality associations, reported as Log Relative Risks (logRR) for the entire exposure lag (30 days), were used to estimate temperature-related mortality. Following Gasparrini et al. [72–74] we assumed that the risk at day t is attributable to a series of exposure events in the past up to a maximum of 30 days. We calculated the attributable number deaths associated with temperature for the present year (1991–2005) using the estimated temperature-mortality rate. The backward attributable fraction ($b - AF_{x,t}$) and thus the backward attributable number ($b - AN_{x,t}$), result from the sum of all contributions in each day, given by the Equations:

$$b - AF_{x,t} = 1 - e^{-\sum_{l=l_0}^{L} \beta_{x_{t-l},l}} \tag{2}$$

$$b - AN_{x,t} = b - AF_{x,t} \cdot n_t$$

where n_t is the number of cases at time t.

2.3.3. Projection of Temperature-Mortality Association

First, the projections of future mortality trends were computed as average daily mortality for every year of the current period (1991–2005) to account for seasonal variations of the historical data [68]. These series were now replicated over the future periods. Finally, temperature-related mortality was calculated to estimate the change in mortality rate per million people for mid-term (2046–2065) and long-term (2081–2099) periods in the both metropolitan areas. Data distribution of current and future periods was explored and is presented in figures. Following, Gasparrini et al. [2], we used the exposure-lag-response curves and estimated temperatures thresholds with projections of future temperatures to estimate the change in mortality attributable to temperature per million people for winter and summer seasons, in the future decades (2046–2065 and 2081–2099).

Assuming the temperature-mortality risk is attributable to a series of past exposure, the sum of the contributions from all the previous days of the series is interpreted as the total excess mortality attributed to non-optimal temperature [2]. The expected mortality changes in hot-related, cold-related, and total temperature mortality rates per million people were presented together with the empirical confidence intervals (eCIs) obtained through Monte Carlo simulations.

2.4. Model Assessment and Sensitivity Analysis

The modified Akaike information criteria for models with over-dispersed data, Quasi-AIC [9,73], was used to examine various df for nonlinear and lag functions for mean temperatures. Sensitivity analyses were performed by changing the df (1–16) per year for time, so as to control for seasonality and trends (Table S1).

All analyses were carried out using the package dlnm [74] in R 3.4.2 statistical software (R Core Team 2017).

3. Results

3.1. Descriptive Statistics

During the study period (1991 and 2005), a total of 159,592 and 74,400 deaths were recorded in Lisbon metropolitan area (LMA) and Porto metropolitan area (PMA), respectively. Table 1 presents the descriptive summaries of baseline mortality rates in the study period. The daily mean deaths in LMA and PMA were 29.13 and 13.58, respectively. There were more deaths in the winter months: 67,349 (42.20%) and 30,138 (40.50%) deaths during the study period - than in the summer months: 44,651 (27.98%) and 20,911 (28.11%) in both metropolitan areas. Overall, the number of deaths among people aged 65+ was 138812 and 65062 in LMA and PMA, respectively, which accounts for the biggest proportion in the two metropolitan areas.

During the study period, the daily minimum and maximum mean temperature for LMA were 3.20 °C and 34.00 °C, respectively, and for LMA, and 1.00 °C and 31.50 °C for PMA, respectively (Table 2). The average daily temperature in winter and summer months for LMA was 12.72 °C and 21.81 °C, respectively, and 11.10 °C and 19.48 °C for PMA, respectively.

Table 1. Descriptive statistics of daily mortality in Lisbon metropolitan area (LMA) and Porto metropolitan area (PMA), 1991–2005.

Metropolitan Area/Age	Season	Mean ± SD	Min.	Percentiles			Max.
				P25	P50	P75	
All ages							
LMA	Total	29.13 ± 8.54	8.0	23	28	34	88
	Summer	24.36 ± 6.29	8.0	20	24	28	88
	Winter	35.32 ± 8.79	11	29	35	41	71
PMA	Total	13.58 ± 4.75	3.0	10	13	16	36
	Summer	11.41 ± 3.59	3.0	9.0	11	14	27
	Winter	16.57 ± 5.01	3.0	13	16	20	36
Age < 65 years							
LMA	Total	3.79 ± 2.11	0.0	2.0	4.0	5.0	14
	Summer	3.43 ± 1.95	0.0	2.0	3.0	5.0	11
	Winter	4.34 ± 2.38	0.0	3.0	4.0	6.0	14
PMA	Total	1.70 ± 1.41	0.0	1.0	1.0	3.0	10
	Summer	1.51 ± 1.29	0.0	1.0	1.0	2.0	7
	Winter	1.98 ± 1.54	0.0	1.0	2.0	3.0	10
Age 65+ years							
LMA	Total	25.34 ± 7.84	7.0	20	24	30	78
	Summer	20.96 ± 5.73	7.0	17	21	24	78
	Winter	31.70 ± 7.65	13	26	31	36	65
PMA	Total	11.87 ± 4.35	1.0	9.0	11	14	33
	Summer	9.90 ± 3.33	1.0	8.0	10	12	23
	Winter	14.62 ± 4.62	2.0	11	14	18	33

Table 2. Descriptive statistics for the mean daily temperatures in Lisbon metropolitan area (LMA) and Porto metropolitan area (PMA), 1991–2005.

Metropolitan Area	Season	Mean	SD	Min.	Percentiles				Max.
					P1	P2.5	P97.5	P99	
LMA	Total	16.90	4.80	3.20	10.80	13.30	26.51	28.20	34.00
	Summer	21.81	2.86	16.10	18.50	19.60	28.60	29.77	34.00
	Winter	12.72	3.42	3.20	8.80	10.60	21.60	23.39	30.20
PMA	Total	15.09	4.42	1.00	9.40	11.80	24.00	26.50	31.50
	Summer	19.48	2.84	12.90	16.30	17.60	26.80	28.27	31.50
	Winter	11.10	2.64	1.00	7.60	9.20	15.80	16.60	18.40

3.2. Temperature-Mortality Association

Table 3 presents the associated risk (logRR) of temperature-related mortality based on daily temperatures for all months, summer and winter months. Across both metropolitan areas, the relative risk for the first percentile and 99th percentile of mean temperature, for LMA and PMA, which shows an increased with exposure to the 1st percentile in winter months. When exposed to maximum temperature (34.00 °C) in LMA, there were significant cumulative (lag 0–30) heat effects for age group 65+ years (logRR = 2.18, 95% CI: 0.19–4.17) and <65 years (logRR = 1.07, 95% CI: −4.12–6.27). However, heat effects were only significant among people aged 65+ years in PMA (logRR = 1.02, 95% CI: 0.04–1.34). On the other hand, with a minimum temperature of 3.20 °C in LMA, and 1.00 °C in PMA, LMA showed a significant cold effect for the elderly (logRR = 7.14., 95%CI: 4.06–18.42) and PMA showed a significant cold effect for the elderly (logRR = logRR = 4.37, 95%CI: 1.52–16.22).

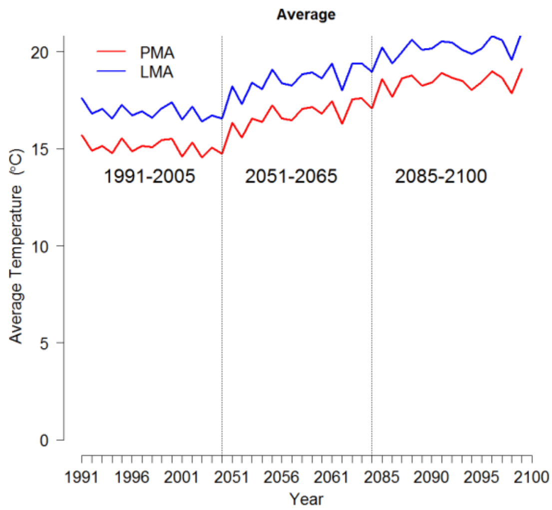
Table 3. Metropolitan areas (MA)–specific relative risk (RR) of mortality due to hot and cold effects, logRR (95%CI), for the period 1991–2005.

MA/Ages	Summer Temperature (99%)	logRR	95% CI		Winter Temperature (1%)	logRR	95% CI	
			Low	High			Low	High
All ages								
Lisbon	29.77	0.09	−0.02	0.19	5.80	**0.64**	**−0.23**	**1.52**
Porto	28.27	0.14	−0.77	1.05	5.20	1.51	−1.10	4.13
Age < 65 years								
Lisbon	29.77	0.20	0.00	0.60	5.80	0.32	−2.09	1.64
Porto	28.27	0.80	0.01	1.59	5.20	**1.45**	**−1.30**	**4.22**
Age 65+ years								
Lisbon	29.77	0.05	−0.04	0.15	5.80	**0.72**	**−0.21**	**1.64**
Porto	28.27	0.14	−0.84	1.12	5.20	**2.17**	**−1.29**	**5.65**
	Summer Temperature (Maximum)	**logRR**	**95% CI Low**	**95% CI High**	**Winter Temperature (Minimum)**	**logRR**	**95% CI Low**	**95% CI High**
All ages								
Lisbon	34.00	**2.03**	**0.15**	**3.93**	3.20	**5.34**	**1.96**	**8.92**
Porto	31.50	1.06	0.42	2.14	1.00	1.65	−0.70	4.01
Age < 65 years								
Lisbon	34.00	**1.07**	**−4.12**	**6.27**	**3.20**	**4.47**	**0.74**	**8.21**
Porto	31.50	0.03	−9.09	9.14	1.00	**1.77**	**−1.54**	**3.1**
Age 65+ years								
Lisbon	34.00	**2.18**	**0.19**	**4.17**	3.20	**7.14**	**4.06**	**18.42**
Porto	31.50	**1.02**	**0.04**	**1.34**	1.00	**4.37**	**1.52**	**16.22**

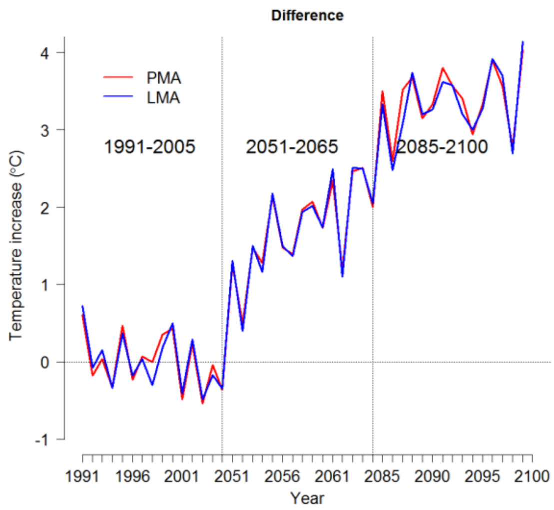
Bold face represents statistically significant risk.

3.3. Projected Exposure and Health Outcomes

In this study, our main interest is the total number of deaths attributable to temperate change in the absence of other changes. The mortality counts were based on average daily deaths per year of the observed data, thereby keeping the seasonality observed in the historical period–1991–2005. Figure 1 shows the temporal trends in temperature for the historical data (1991–2005) and projected future periods (2051–2065 and 2081–2099). The time series plot indicates an increasing trend in average temperature in both metropolitan areas over the century (Figure 1a).



(a)

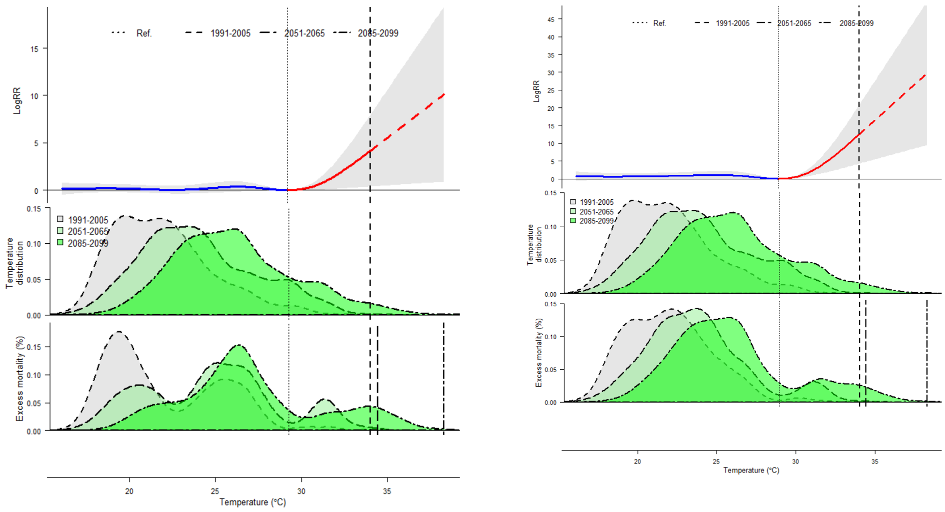


(b)

Figure 1. Time series plot of temperature in the PMA (Porto metropolitan area) and LMA (Lisbon metropolitan area) for the present/current period, 1991–2005 and future projections 2051–2065 and 2085–2099, (**a**) Average temperature, (**b**) Difference in temperature from historical average (1991–2005).

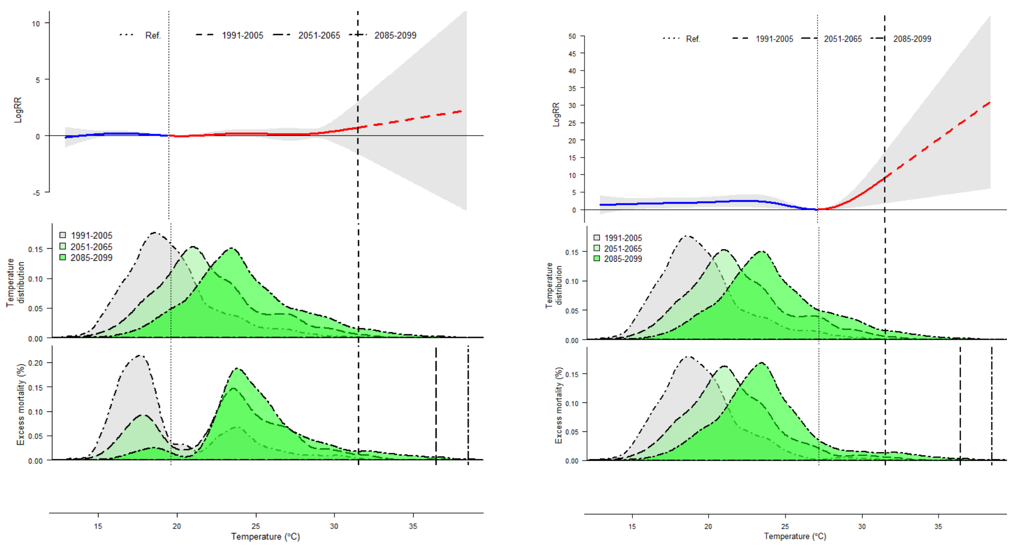
The temperature in LMA is estimated to increase from a yearly mean of 16.89 °C in 1991–2005 to a yearly mean of 18.61 °C and 20.25 °C in future periods 2051–2065 and 2085–2099, respectively. In the same vein, temperatures in PMA are estimated to rise from 15.09 °C in the current period to 16.81 °C and 18.50 °C in the future periods, respectively. The differences observed in these future temperatures are depicted in the Figure 1b.

The top panel of Figures 2–5 display the estimated temperature–mortality relationship for the historical period and the future periods. The exposure-response curve is extrapolated to capture the future temperature projections. There is a general observation that the estimate mortality risk is set to increase with warmer temperatures in the future periods, compared to historical period (Figures 2 and 3). This is clearly observed as the red dash lines increase with warmer temperatures, especially during the summer in the future periods (Figures 4 and 5).



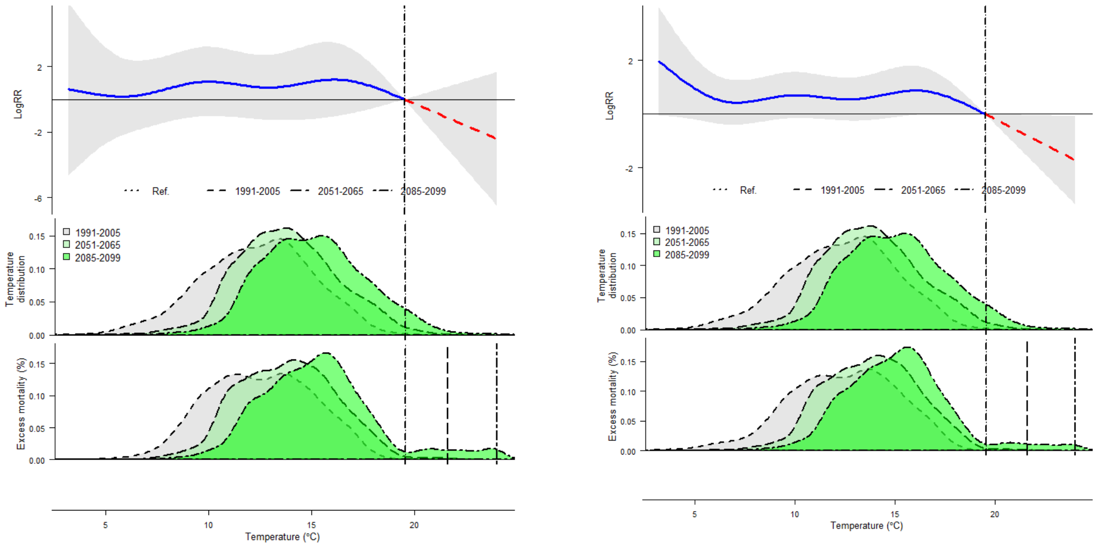
(**a**) (**b**)

Figure 2. Temperature related mortality and excess mortality for the present and projected future periods in Lisbon metropolitan area (LMA) during the summer period for people aged <65 years (**a**) and 65+ years (**b**). Top panel: Exposure-response curve for temperature-mortality cumulative associations (logRR). The solid lines represent the logRR and the gray areas the 95% empirical confidence interval. The dotted vertical line corresponds to reference temperature (MMT) which divides the curve into cold and hot (blue and red lines, respectively). Middle panel: distribution of temperature values for the present period, 1991–2005 (grey area) and future periods, 2051–2065 (green area) and 2085–2099 (darker green area). Bottom panel: distribution of temperature-related excess mortality, expressed as the fraction of additional deaths (%) attributed to non-optimal temperature, compared with the reference temperature.



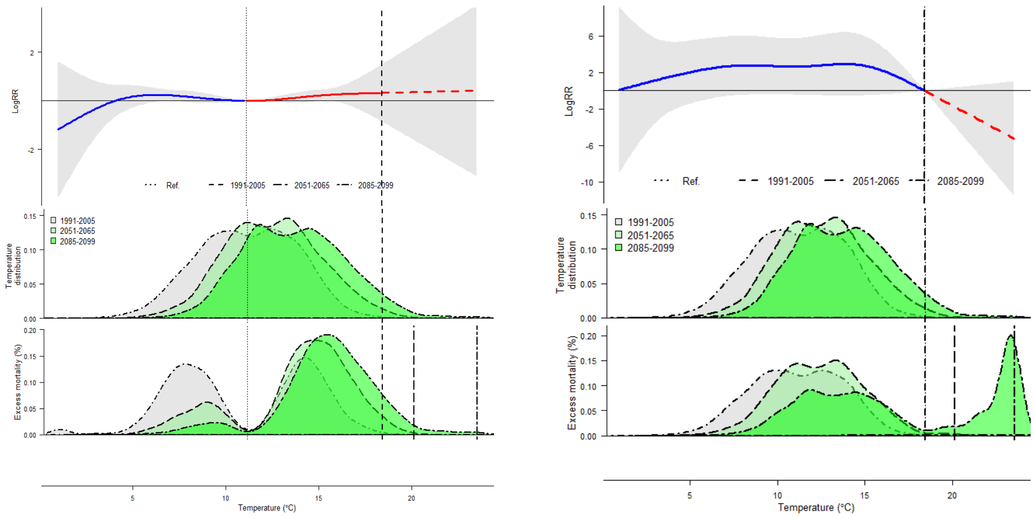
(**a**) (**b**)

Figure 3. Temperature related mortality and excess mortality for the present and projected future periods in Porto metropolitan area (PMA) during the summer period for people aged <65 years (**a**) and 65+ years (**b**). Top panel: Exposure-response curve for temperature-mortality cumulative associations (logRR). The solid lines represent the logRR and the gray areas the 95% empirical confidence interval. The dotted vertical line corresponds to the reference temperature (MMT) which divides the curve into cold and hot (blue and red lines, respectively). Middle panel: distribution of the temperature values for the present period, 1991–2005 (grey area), and future periods, 2051–2065 (green area) and 2085–2099 (darker green area). Bottom panel: distribution of temperature-related excess mortality, expressed as the fraction of additional deaths (%) attributed to non-optimal temperature compared with the reference temperature.



(a) (b)

Figure 4. Temperature related mortality and excess mortality for the present and projected future periods in Lisbon metropolitan area (LMA) during the winter period for people aged <65 years (**a**) and 65+ years (**b**). Top panel: Exposure-response curve for temperature-mortality cumulative associations (logRR). The solid lines represent the logRR and the gray areas the 95% empirical confidence interval. The dotted vertical line corresponds to reference temperature (MMT) which divides the curve into cold and hot (blue and red lines, respectively). Middle panel: distribution of the temperature values for the present period, 1991–2005 (grey area), and future periods, 2051–2065 (green area) and 2085–2099 (darker green area). Bottom panel: distribution of temperature-related excess mortality, expressed as the fraction of additional deaths (%) attributed to non-optimal temperature compared with the reference temperature.



(**a**) (**b**)

Figure 5. Temperature related mortality and excess mortality for the present and projected future periods in Porto metropolitan area (PMA) during the winter period for people aged <65 years (**a**) and 65+ years (**b**). Top panel: Exposure-response curve for temperature-mortality cumulative associations (logRR). The solid lines represent the logRR and the gray area the 95% empirical confidence interval. The dotted vertical line corresponds to reference temperature (MMT) which divides the curve into cold and hot (blue and red lines, respectively). Middle panel: distribution of the temperature values for the present period, 1991–2005 (grey area) and future periods, 2051–2065 (green area) and 2085–2099 (darker green area). Bottom panel: distribution of temperature-related excess mortality, expressed as the fraction of additional deaths (%) attributed to non-optimal temperature compared with the reference temperature.

However, the estimated mortality risk decreases in the winter in the future periods (Figures 4 and 5). The distribution of temperature values throughout the historical and future periods is presented in the middle panels of Figures 2–5. It is evident that temperatures in both metropolitan areas show a slight difference, with PMA exhibiting lower temperatures than in LMA. In the future periods, it is projected that winter will get warmer (middle panels of Figures 4 and 5) and summer will get hotter (middle panel of Figures 2 and 3).

The estimated burden of temperature-attributable mortality (%) in the historical period (1991–2005) and future periods 2051–2065 and 2085–2099 are presented in Table 4. We estimate a decrease in extreme cold-related deaths of 0.55% and 0.45% in LMA, for 2051–2065 vs. 1991–2005 and 2085–2099 vs. 1991–2005, respectively (Table 4). Similarly, in PMA there is a decrease in cold-related deaths of 0.31% and 0.49% for 2051–2065 and 2085–2099, compared to 1991–2005. LMA is expected to have an overall increase in extreme heat-related deaths of 1.04% and 0.44% in 2051–2065 and 2085–2099, respectively, compared to the historical period (1991–2005). The burden of heat-related mortality (during the summer months) is estimated to increase substantially over the future periods, compared to the current period for all ages, being higher among people 65+ years. For example, in LMA, during the summer months, there is an increase for all ages in extreme heat-related deaths of 1.58% and 0.10% for the two periods, compared to the historical period. The burden of extreme heat-related mortality in the 65+ years age group is slightly higher than in age group <65 years, at 2.22% vs. 1.38% for 2085–2099, compared to the historical period. However, in PMA, only people aged 65+ years showed a significant temperature-related burden of deaths that can be attributable to hot temperatures. The heat-related excess deaths increased from 0.23% for 2051–2065 to 1.37% for 2085–2099, compared to the historical period.

Table 4. Changes in temperature-attributable mortality (%) in the future periods (2051–2065 and 2085–2099) vs. 1991–2005, with their 95% empirical confidence interval.

Metropolitan Area/Age	Period	Extreme Cold	Extreme Heat
		LMA	
All ages			
All year	2051–2065 2085–2099	**−0.55 (−0.71 to −0.40)** **−0.45 (−0.57 to −0.33)**	**1.04 (0.55 to 1.47)** **0.44 (0.19 to 0.67)**
Summer [1]	2051–2065 2085–2099		**1.58 (0.75 to 1.90)** **0.10 (0.04 to 0.14)**
Winter [2]	2051–2065 2085–2099	−0.67 (−1.19 to 0.59) 0.79 (−1.39 to 0.69)	
<65 years			
Summer [1]	2051–2065 2085–2099		**0.08 (0.11 to 0.21)** **1.38 (1.67 to 2.37)**
Winter [2]	2051–2065 2085–2099	−1.15 (−3.11 to 49.01) −1.39 (−3.76 to 53.11)	
65+ years			
Summer [1]	2051–2065 2085–2099		**0.10 (0.00 to 0.18)** **2.22 (0.11 to 1.82)**
Winter [2]	2051–2065 2085–2099	**−1.41 (−2.53 to 1.50)** **−1.67 (−3.05 to 1.10)**	

Table 4. *Cont.*

Metropolitan Area/Age	Period	Extreme Cold	Extreme Heat
		PMA	
All ages			
All year	2051–2065 2085–2099	**−0.49 (−1.00 to 0.05)** **−0.31 (−0.57 to −0.01)**	0.39 (−0.14 to 0.88) 0.14 (−0.10 to 0.37)
Summer [1]	2051–2065 2085–2099		0.08 (−0.24 to 0.21) 0.57 (−1.10 to 1.15)
Winter [2]	2051–2065 2085–2099	−1.13 (−1.47 to 3.49) −1.34 (−1.74 to 4.16)	
<65 years			
Summer [1]	2051–2065 2085–2099		0.06 (−0.35 to 0.20) 0.39 (−2.01 to 1.12)
Winter [2]	2051–2065 2085–2099	−0.28 (−0.58 to 0.96) −0.32 (−0.68 to 0.85)	
65+ years			
Summer [1]	2051–2065 2085–2099		**0.23 (0.05 to 0.28)** **1.37 (0.41 to 1.52)**
Winter[2]	2051–2065 2085–2099	**−1.35 (−1.51 to 17.84)** **−1.58 (−1.75 to 17.79)**	

[1] Extreme heat above 99th percent. [2] Extreme cold less than 1st percentile. Bold face represents statistically significant risk.

4. Discussion

This study projects the number of deaths attributable to temperature according to diseases of the circulatory system and age group (under 65 years and 65+ years), using future daily temperature simulated by the weather research and forecasting (WRF) model, a distributed lag non-linear model with a quasi-Poisson family. This was conducted for two metropolitan areas in Portugal (Lisbon and Porto).

The results reported in this study indicate that the baseline temperature-mortality relationships for cold and hot temperatures contributed to an increased risk of mortality. However, substantial mortality burdens are visibly attributable to cold temperatures in Lisbon and Porto metropolitan areas, during the historical period. According to recent studies in Portugal [1,9,20,68], winter mortality is higher than summer mortality, especially among people aged 65 years and older with cardiovascular or higher prevalence of individuals with chronic diseases. Various underlying mechanisms have been proposed to explain the mortality risk associated with exposure to high and low temperatures. Previous studies have shown plausible physiological mechanisms for these relationships. Regarding high temperatures, mortality risks may be caused by failure of thermoregulation, which may be impaired by dehydration, salt depletion, increased surface blood circulation, and elevated blood viscosity during the hot season [75–77]. Low temperatures increase the risk of thrombogenic complications by inducing well-known and relatively rapid changes in blood composition, such as platelet viscosity, blood cholesterol, and blood pressure [78–82], which may increase the risk of myocardial infarction and stroke [83]. According to other studies, the magnitude of associations varies according to several characteristics, such as population structure, level of education, pre-existing conditions, socioeconomic status, housing conditions, access to health care, nutrition status, race, and ethnicity, which can affect the vulnerability to extreme temperatures [10,11].

Results also revealed that, in future projections, the proportion of burdens attributable to the effects of heat has a higher order of magnitude than for the cold. A decrease is estimated in extreme cold-related deaths of 0.55% and 0.45% in LMA for 2051–2065 and 2085–2099, respectively. In PMA, there is a decrease in cold-related deaths of 0.31% and 0.49% for 2051–2065 and 2085–2099, respectively. Our findings agree with previous studies estimating the magnitude of temperature effects on mortality. Gasparrini et al. [2] analyzed the impact of extreme temperatures under different climate change scenarios over a long-time horizon, 2090–2099, having concluded that southern European regions are going to experience an increase in hot-related mortality as well as a clear decrease in cold-wave-related mortality. For example, a study by Hajat et al. [84], based on modeled daily temperature projections for the whole of the UK, estimated an increase in annual heat-related deaths over the 2020s–2050s and 2050s–2080s, and corresponding decreases in cold-related deaths. In a study about Canada, Cheng et al. [85] projected that hot-related mortality would more than double by the 2050s and triple by the 2080s, estimating as well that cold-related mortality would decrease by 45–60% by the 2050s and by 60–70% by the 2080s, in four Canadian cities. On the other hand, according to climate change projections by Baccini et al. [86], the highest impact in Europe will be in three Mediterranean cities (Barcelona, Rome, and Valencia) and in two continental cities (Paris and Budapest), due to high summer temperatures. This study also estimates that, in terms of age, the highest impact will be in people aged 75 years and older. However, in some cities, a relatively high rate of hot-related deaths is estimated in young adults.

Southern Europe and the Iberian Peninsula are pointed out as one of the European regions most likely to be affected by climate change, facing a diversity of potential impacts such as more frequent heat-related events, which are expected to increase over the next decade in terms of intensity, magnitude, and spatial extent [21]. Increases in morbidity and mortality are therefore expected. Understanding the possible magnitude of future adaptation needs could facilitate identifying interventions to increase population health resilience in a future climate [22,87]. For that reason, adaptation measures will need to be developed, particularly in metropolitan areas, in order to quantify and explain excess deaths related to high temperatures in an increasingly older population. Even though Lisbon and Porto are cities with frequent heatwave events, older people and children are still not acclimatized to extreme heat, which increases temperature-related mortality. These measures could consist of identifying disease thresholds; interfacing with emergency preparedness; reinforcing population monitoring processes, particularly of the most vulnerable people; reinforcing alert systems for cold weather and heatwave plans; improving the knowledge on local vulnerabilities; and including projections of climate change health impacts under different climates so as to identify impacts on mortality of all magnitudes and formulate public health policies. Cities are particularly vulnerable to the effects of climate change due to their location, increasing urbanization, infrastructures, as well as social and economic inequalities [88–90]. Urban planning is strongly associated with population health, which should be protected today and in the future. At a local level, it is crucial that urban planning addresses climate mitigation and adaptation issues, aiming towards a sustainable development. For example, by creating green spaces for leisure that intersperse grassed open areas with spaces with trees and shading, where aeration is simple, and by improving the thermal behavior of buildings.

Some limitations of this study must be acknowledged. First, we did not take into account the future changes in the demographic structure, which may result in an underestimate of the health impact of climate change. Population trends can be interrelated and may intersect across different susceptibilities, with potential growth in different subgroups with varying sensitivities. Since subpopulations respond to hot differently with respect to mortality risk, any increase in total population density or in the proportion of vulnerable subpopulations may tend to change population characteristics and affect the relative impact of hot in the future [2,91,92]. Second, there is a need to be cautious with the interpretation of the projected temperature-related impact. Our approach to estimate future changes to temperature-related mortality is based on temperature-mortality rates estimated using historical data to model future temperature series. The attributable number of deaths was computed using the historical mortality data averaged over the observed time series. Third, the choice of smoothing functions for the exposure-lag-response relationships are difficult to validate in DLNM. In this study we based our choice on model selection criteria (QAIC). In spite of these limitations, the assumptions made in this study are reasonable in the absence of adequate information and do not reduce the importance of our findings.

5. Conclusions

To conclude, this study showed that, for the future periods (2051–2065 and 2085–2099), projections indicate that winters will be warmer and summers will be hotter. The estimated mortality risk is expected to increase with warmer temperatures in the future periods, compared to the historical period. For all ages, the proportion of burdens attributable to hot effects is much higher than the burden attributable to cold in both metropolitan areas, especially in the future periods. In LMA, the burden of extreme hot-related mortality in age group 65+ years is slightly higher than in age group <65 years, for 2051–2065 and 2085–2099. However, in PMA, only people aged 65+ years showed significant temperature-related burden of deaths that can be attributable to hot temperatures.

Our study provides results which may be beneficial to healthcare providers when developing long-term management plans, contributing as well to the development and implementation of public health policies, strategic initiatives contemplating the future distribution of the health resources necessary to control mortality due to diseases of the circulatory system in Portuguese metropolitan areas. Lastly, further research is required in order to understand vulnerabilities associated with poverty, social isolation, and outdoor workers.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4433/11/2/159/s1, Table S1. Model assessment based on degrees of freedom for trend and crossbasis function.

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