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ORIGINAL ARTICLE

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Heat stress and mortality in Lisbon Part I. model construction and validation

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Abstract Global climate change will have direct impacts on human health, including increased mortality due to heat stress and heat waves. An empirical-statistical model for heat stress is constructed for the city of Lisbon using the June–August months of the observational period 1980–1998. The model uses the regression of an aggregate dose-response relationship between maximum temperature and excess heat-related deaths, based on the difference between observed and expected deaths. The model is validated by correlation and residual analysis. The mean annual heat-related mortality for the period 1980–1998 was between 5.4 and 6 deaths per 100,000 depending on the method used to calculate expected deaths. Both validation methods show that the model has a moderate to high accuracy in modelling heat-related deaths compared to the observed record.

Keywords Heat-related deaths · Climate · Mortality · Heat stress · Heat waves · Lisbon

Introduction

Excessive heat is a well-known cause of heat stress, exacerbated illness and mortality. Many epidemiological studies have confirmed this, including case–control studies (e.g. Kilbourne et al. 1982; Semenza et al. 1996), ecological studies (e.g. Rooney et al. 1998; Smoyer 1998) and even some experimental studies (e.g. Keatinge et al. 1986). It has been observed that meteorological variables can have a significant impact upon the physical processes mediating thermal homeostasis. Illnesses recognisable as the direct result of exposure to prolonged periods of high environmental temperature are heatstroke, heat exhaustion, heat syncope and heat cramps (Kilbourne 1997).

Heat waves have readily discernible health impacts because they result in a large number of deaths and affect relatively large, heterogeneous areas simultaneously. Not all heat waves have a similar impact on mortality. In addition to the intensity of a heat wave, the duration and timing of the event are particularly important (Smoyer 1998). The public health impact of heat depends not only on the weather conditions at the time but also on previously existing conditions. A delay between the onset of the heat wave and the appearance of substantial adverse effects on public health has been observed (Kilbourne 1997). The mortality increases observed during heat waves disproportionately affect the elderly, the young, people with pre-existing illnesses and low-income groups, especially in large urban areas (Kilbourne 1997). Most studies focus on urban environments because heat waves have a bigger impact in cities as a result of the so-called urban heat island effect (Oke 1987).

Lisbon is the largest city in Portugal and lies on the north bank of the Tagus estuary, on the European Atlantic coast. Portugal is a country with a mild climate, a small population (9.9 million) and comparatively low per capita GDP. Approximately 600,000 people live in the city of Lisbon. However, the focus of this paper is on the district of Lisbon (an area of 2,795 km^2), which includes various satellite towns, raising the population to approximately 2 million people.

Recent studies have shown that Portugal, including Lisbon, is vulnerable to the impacts of global climate change (dos Santos et al. 2002). It is expected that climate change will have mostly adverse impacts on human health, with significant loss of life (Watson et al. 1996). Many of the health impacts of climate change will occur via relatively direct pathways (e.g. deaths from heat waves and from extreme weather events); others will occur via indirect pathways (e.g. changes in the range of vector-borne diseases) (McMichael et al. 1996b; McMichael et al. 2001). Here I focus on the health impacts of heat stress and heat waves. An increased frequency or severity of heat waves would cause an increase in mortality and illness (McMichael et al. 1996b).

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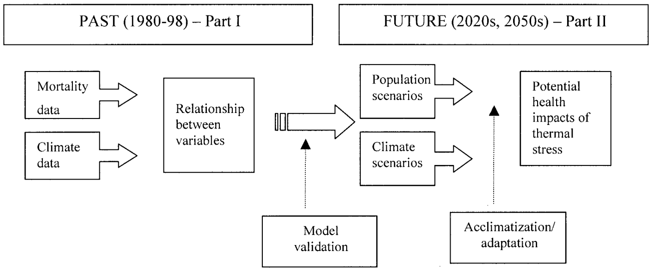

Fig. 1 Schematic representation of the method used in this study

Some studies show that, by the middle of the century, summer heat-related mortality could increase dramatically (Donaldson et al. 2001; Duncan et al. 1997; Kalkstein and Green 1997) but others conclude that the expected changes in mortality will be minor (Guest et al. 1999) or temporary (Keatinge et al. 2000).

I aimed to determine whether climate change will increase heat-related mortality in the city of Lisbon. This work is being published in two parts (Fig. 1). In Part I, the past relationship between climatic extremes and mortality in the district of Lisbon from 1980 to 1998 is examined. On the basis of the difference between observed and expected deaths, an aggregate dose-response relationship for heat-related mortality was established through regression methods. I also validated the model using correlation and residual analysis. Part II will apply the relationship described in this paper to future climate and population scenarios to assess the potential impacts on public health. An uncertainty analysis has also been performed to provide a probabilistic estimate of future heat-stress mortality for Lisbon.

Materials and methods

All-cause daily mortality data for the district of Lisbon (1980–1998) were acquired from the Portuguese National Institute of Statistics (Instituto Nacional de Estatística – INE), together with estimates of the past resident population in Lisbon. I estimated resident population data for the 1980s by interpolating between the census years of 1981 and 1991. Since the total population of Lisbon has not changed significantly in the past 20 years, I present most of the results in terms of raw mortality (considering Lisbon's population at a constant level of 2.05 million people). Standardisation of the mortality data for age was not performed because the data were not available at an affordable cost, therefore the results should be considered with caution because of the effects of the ageing population.

Daily climate data were provided by the Portuguese Meteorology Institute for the period under study. Variables included maximum, minimum and average temperatures, and relative humidity for one weather station in the capital city (Lisboa Geofísico). The station is located in the centre of the city of Lisbon, which is in the south of the district of Lisbon, the maximum distance to the district border being around 65 km. I considered this station representative of the whole district. However, this is problematic because the weather station could be kilometers away from where the deaths occurred, but more importantly, outdoor measurements do not necessarily reflect the variable conditions within dwellings and other buildings in which most of the deaths occur (Kilbourne 1997). This is a very difficult problem to overcome because of the lack of meteorological data at the necessary scale.

An observed/expected analysis was conducted, similar to one of the methods used by Guest et al. (1999). Two approaches were taken to calculate excess deaths, i.e., deaths beyond those expected for that period in that population. First, I used a fixed mean of daily mortality for each summer month, for the period 1980–1998 (50.5 deaths in June, 49.9 in July and 47.6 in August). Second, I used a 30-day running mean between mid-May and mid-September, which smoothes the fluctuations in the data, but selected only the summer values. In each case, daily excess deaths were calculated by subtracting the expected values from the observed daily values. For the fixed-mean approach, that meant subtracting every observed daily death of June from 50.5, every observed daily death of July from 49.9 and so on. In the 30-day running-mean method, from each observed daily death its corresponding expected value was subtracted.

Heat-related deaths were defined as the number of deaths occurring in excess of the number that would have been expected for that population in the absence of stressful weather (McMichael et al. 1996a). Each number of excess deaths was then grouped into the corresponding 1 °C interval for simplification purposes (common in an ecological study design). For example, if on the 16th of August the maximum temperature was 32.7 °C and there were 5 excess deaths, 5 would be put in the 32–32.9 °C interval. I postulated that an unknown proportion of deaths associated with temperatures above a certain threshold would be unrelated to climate while many deaths associated with temperatures below the threshold may actually have had a casual relationship with climate. Therefore, I added all excess deaths in each 1 °C interval for the entire period to find out where heat-related deaths were no longer detectable; in this way only temperatures over a certain threshold were regressed. This level of aggregation was necessary because no statistically significant relationship could be established when each excess death was plotted against its corresponding maximum temperature. Finally, the sum of the excess deaths in each interval was divided by the frequency of occurrence of that temperature interval in the 1980–1998 period to give the number of deaths per day for a particular temperature interval. For example, if there were 60 deaths in the 38 °C interval (the sum of all excess deaths, positive and negative, that occurred when the temperature was between 38 °C and 38.9 °C) this value would be divided by 7, the number of times this temperature interval was observed in the period 1980–1998. The aggregate climate-mortality relationship was not linear, so a non-linear regression method of the type $y = ae^{bx}$ (where y is the heat-related mortality per day, x the maximum temperature interval and a and b are constants) was used to establish the association. This provided a relationship between climate and heat-related mortality in Lisbon for the summer months of 1980–1998.

The testing of predictive models is, arguably, the most critical stage of an impact assessment (Parry and Carter 1998). In order to validate the model, I split our daily mortality data (1980–1998) into two samples, hereafter referred to as 1980s (1980–1989) and 1990s (1990–1998). I established associations between mortality and climate for both periods using the same observed/expected analysis and the regression methods described above. I only performed this for the fixed-summer-means approach for simplicity. Each function was applied to the daily temperature series of the other time slice (with no, 1 and 2-day lags), and observed and modelled data were compared by using the correlation between predicted and observed values (following Stewart 2000), through a residual analysis and regression coefficient.

Results

A time series plot of the all-cause daily mortality rate for the district of Lisbon (1980–1998) shows a clear seasonal variation of mortality: high in winter and low in summer (Fig. 2). This is most noticeable in the smoothed line, which represents a 30-day running mean. Also visi-

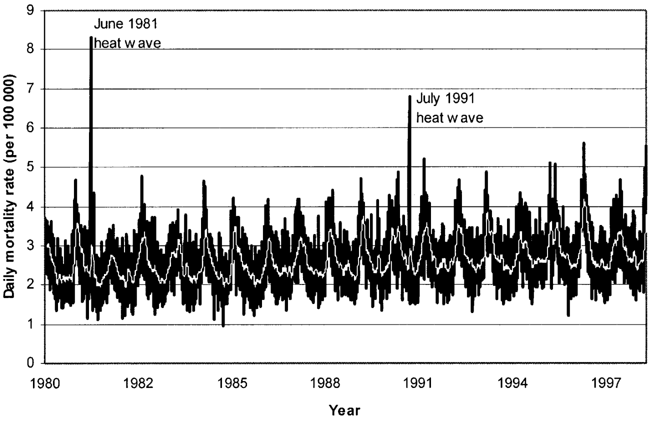

Fig. 2 Daily mortality rate for Lisbon 1980–1998. *White line* (within the black line) is a smoothed 30-day running mean

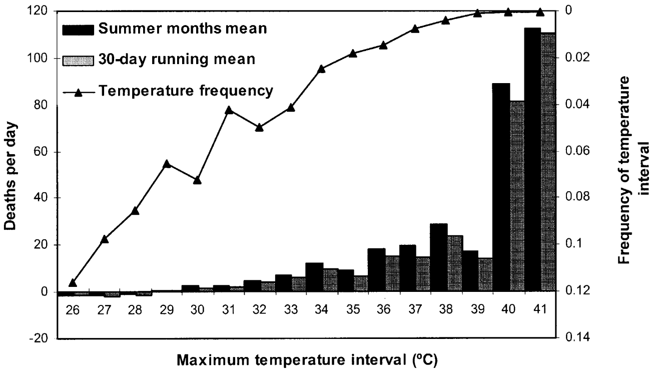

Fig. 3 Summer deaths per day for each temperature interval for Lisbon during the period 1980–1998, using a 30-day running mean, and a summer-months mean to produce the expected mortality values. ▲ The frequency of occurrence of the temperature interval during the period

ble are the spikes of 1981 and 1991, which were confirmed, in the literature (Carvalho 1999; Falcão et al. 1988; Garcia et al. 1999) to have been affected by intense heat waves.

A V-shaped relationship (also referred to as U-shaped) between mortality and temperature has been observed in several studies (cf. Kalkstein 1993; Kunst et al. 1993). In Lisbon, this appeared more like a horizontally stretched U (not shown), with a large comfort zone: the days of lowest mortality (below 30 deaths a day) occurred between 15.6 °C and 31.4 °C.

The observed/expected analysis, under both approaches, showed that hotter days were associated with greater mortality risk (Fig. 3). It becomes clear that the 30-day running-mean approach gives a more conservative estimate of excess deaths than the fixed-summer-months mean. Both approaches were consistent in showing that heat-related deaths were not discernible below 29 °C. Substantial heat-related deaths, however, occurred at very high temperatures (e.g., over 40 °C). The temperature interval/frequency curve shows that very high maximum temperatures rarely occurred in the 1980–1998 period (e.g., both the 40 °C and 41 °C intervals were only observed once, hence the low frequency).

Table 1 Regression coefficients and R^2 obtained by using the summer-months mean and the 30-day running mean for the whole period and the summer-months mean for the 1980s and 1990s

Period	Approach	*a*	*b*	R^2
Whole period	Summer-months mean	0.00002	0.3744	0.9607
	30-day running mean	0.000005	0.4113	0.9485
1980s	Summer-months mean	0.00004	0.3601	0.7646
1990s	Summer-months mean	0.00006	0.3422	0.8741

Table 2 Observed mortality and that given by two variants of the model (using a summer-months mean or a 30-day running mean) for 1980–1998. Mortality rates per year (per 100,000 population) are given in parentheses using the average population throughout the period

Data source	Deaths 1980–1998	
	Summer-months mean	30-day running mean
Observed	2,425 (6.2)	1,903 (4.9)
Modelled	2,338 (6.0)	2,108 (5.4)

The non-linear regression of excess deaths per day above 29 °C (in 1 °C intervals) by its temperature interval led to the associations shown in Table 1. These functions were found to be statistically significant ($P < 0.00$) and with a high R^2, partially due to the high aggregation level of combining excess deaths into 1 °C intervals.

Different methods of calculating expected deaths led the summer-months-mean approach to underestimate deaths slightly, whereas the running-mean approach overestimated deaths (Table 2). Under the first variant, the total annual heat-related mortality was around 6 per 100,000 or 128 deaths per year for the population of Lisbon, during the period 1980–1998.

For validation purposes, I applied the observed/expected analysis to the two sets of data designated 1980s and 1990s, and fitted separate regressions over 29 °C (the observed threshold for both periods) to each set of data to establish climate-mortality associations. The relationship coefficients and R^2 are presented in Table 1 and graphically in Fig. 4. I ran each function with the temperature series of the other time period and found a moderate to high accuracy between modelled and observed values. Accuracy is here defined as the correlation between that which is predicted and that which actually occurs (Stewart 2000). The correlation between samples was 0.96 for the 1980s and 0.88 for the 1990s. These values were obtained using excess death values aggregated in 1 °C intervals. When each observed temperature value was used (instead of temperature intervals), the correlation dropped to 0.52 and 0.53, but was still significant at the 1% level. This showed that the association regressed for the 1990s, at the aggregate level, was slightly better at predicting mortality during the 1980s than vice versa.

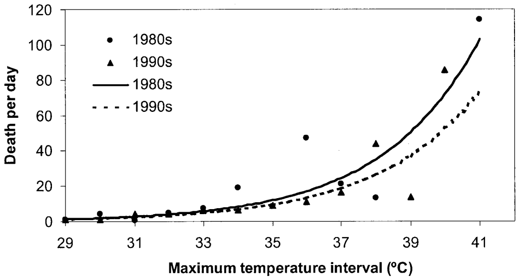

Fig. 4 Summer deaths per day for each temperature interval for Lisbon, for 1980s (1980–1988) and 1990s (1988–98), using the summer-months means as expected mortality values. ––, – – – The relationships established for each period

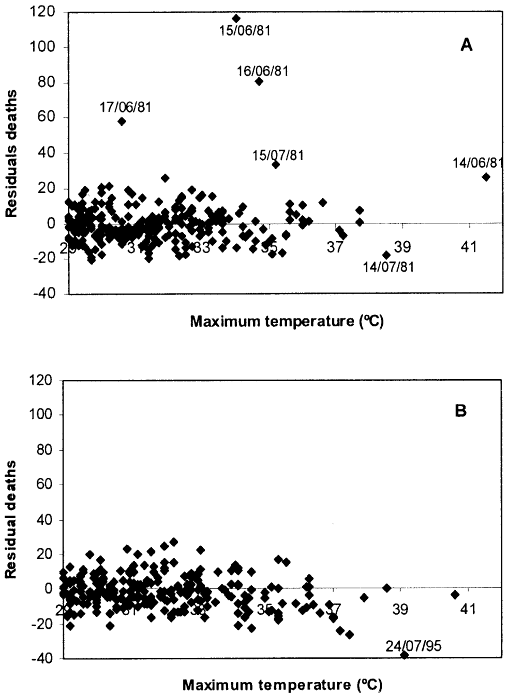

Fig. 5A, B Residual plots from simple regression of heat-related deaths for maximum temperature: (**A**) using the 1990s climate–mortality association to predict 1980s heat-related mortality, (**B**) using the 1980s climate–mortality association to predict 1990s heat-related mortality. The furthest outliers show their dates of occurrence

Another approach used to determine the model's reliability was residual analysis. I calculated the difference between the predicted heat-related mortality for each temperature recorded and the observed heat-related mortality. For the 1980s the outliers were confirmed to be a result of the June 1981 intense heat wave (Fig. 5A). The day of maximum heat (14 June 1981) reached 41.5 °C, but the mortality predicted by the 1990s model was short by about 40 deaths. During the next day (15 June) the maximum temperature dropped by 7.5 °C increasing slightly the following day (16 June), but the mortality continued to increase. Several studies have observed a delay between the onset of a heat wave and the appearance of noticeable increases in mortality. Because of this, I also modelled heat-related mortality with a 1- and 2-day lag period (Table 3). For both periods, a 1-day lag slightly improved the standard deviation of residuals, but a 2-day lag increased either the mean or the standard deviation.

Table 3 Residual mortality (mean and standard deviation) for each period considering no, 1- and 2-day lags between the observed temperature and the modelled mortality

Lag	1980s (as modelled by 1990s)		1990s (as modelled by 1980s)	
	Mean	Standard deviation	Mean	Standard deviation
No lag	0.6	13.2	–1.6	9.8
1-day lag	1.5	11.7	–0.1	9.5
2-day lag	2.3	13.2	1.0	10.9

The 1990s, as modelled by the 1980s, showed a slightly better performance, with a residual standard deviation of 9.8 deaths. Interesting to note is the furthermost outlier in this period (Fig. 5B). Further examination of the temperature series showed that it was a result of a short-term increase in temperature. Maximum temperatures increased from 28.2 °C (22 July 1995) to 39.1 °C (24 July 1995) and then suddenly dropped to 25.4 °C (26 July 1995).

Discussion

I have shown that there is a strong association between mortality and maximum temperature in Lisbon for the summer months of 1980–1998. However, modelling heat-related deaths is not a straightforward exercise.

The foundation of this empirical-statistical model is the calculation of heat-related deaths. These were considered to be the number of deaths occurring in excess of the number that would have been expected in the absence of heat stress. This approach was taken because it allowed us to determine objectively the temperature threshold where heat-related deaths were no longer discernible, instead of using an expert judgement based on a climatological threshold. However, the fact remains that there is no consensus on how to estimate expected deaths. It is interesting to note that the 30-day running-mean model produced more deaths than the other approach in a few cases. One would expect that the 30-day running-mean approach would be more influenced by a heat wave, thus bringing down the number of excess deaths. In fact this does occur, but only to a certain extent because the regression exercise distorts part of the relationship because of the aggregation into temperature intervals. This leads me to question how valid this aggregation really is.

I have extended the dose-response curves (not shown) by an extra 2 °C to demonstrate the sensitivity of mortality to increasing temperatures under the two models (this is also relevant to part II, where future climate scenarios

Table 4 Maximum temperature statistics (mean, standard deviation, maximum and minimum) for each period (1980s and 1990s) and average, minimum and maximum temperatures for the June 1981 and July 1991 heat waves comprising the length of time over 29 °C of maximum temperature surrounding the highest value recorded

Value	T_{max} (°C)		1981 heatwave			1991 heatwave		
	1980s	1990s	T_{av} (°C)	T_{min} (°C)	T_{max} (°C)	T_{av} (°C)	T_{min} (°C)	T_{max} (°C)
Mean	26.8	27.0	28.0	22.1	34.4	27.9	15.5	34.5
SD	3.8	4.0	3.2	3.0	3.7	3.4	1.2	3.7
Maximum	41.5	40.6	34.5	27.6	41.5	34.0	17.7	40.6
Minimum	16.7	17.5	25.0	17.9	30.6	23.8	13.2	29.5

are applied). At temperatures lower than 38 °C the 30-day running mean is always lower than that of the summer months, but above this point it grows more quickly than the latter. This leads me to conclude that, while the model might not be too sensitive to these two parameters in its present range, outside this range differences start to increase rapidly. At 43 °C, the 30-day running-mean approach mortality is 20% higher than the other approach. If I assume the dose-response relationship can be extended, this could have substantial implications. Further investigation is needed in this area. For example, it would be interesting to see how the model would behave under global climate change or to test the sensitivity to other methods of estimating heat-related deaths.

The method I have described appears to have favoured moderate heat over extreme heat (i.e. heat waves) with some of our model assumptions. The 1981 and 1991 heat waves account for between 23% and 30% of all heat-related deaths in the 1980–1998 period. Only the application of different methods will provide comparisons. I also performed a multiple regression of the entire period without any sort of aggregation (not shown), which showed that, when only summer maximum temperatures above 31.4 °C are considered, weather variables could explain 34% of the variability in mortality. The variables, all significant at the 1% level, consisted of seasonality (i.e. if early or late in the summer), maximum temperature and diurnal temperature range ($T_{max} - T_{min}$). Relative humidity did not prove significant, probably because of the prevalence of dry hot air masses that affect Lisbon during the summer. Both the seasonality and diurnal temperature range had negative coefficients, showing that mortality was higher earlier in the season and when the temperature range was lower. This shows that people are sensitive to a low diurnal range and that seasonal acclimatization might occur in Lisbon, as observed in other cities. This could also be due to the phenomenon of "harvesting", where the persons who died under extreme heat would have died anyway in the near future whatever the temperature. This "mortality displacement" is relatively recognizable in both the 1981 and 1991 heat waves in the form of lower than normal (expected) crude mortality.

The model used in this study does not take these multiple parameters into account, which could mean it overestimated deaths by not considering them explicitly. However, this is implicit in the two approaches I used to calculate heat-related deaths, in particular in the 30-day running mean, which is more influenced by seasonal mortality. Even so, I must recognize that a single-variable analysis, such as this one, only accounts partially for the impact of climate on human health, but as others have concluded (cf. WISE 1999), temperature is the dominant climate predictor of death rates in Europe. Also implicit in the decision to use only one variable was that the procedure should be kept relatively simple for the application with future climate scenarios in part II.

To validate the model I broke the study period (1980–1998) into two, one period providing the climate/mortality association for the other to predict. The results showed the relationships were both valid. The more comprehensive (residual) analysis yielded important characteristics of the model that need to be taken into consideration when interpreting the prospective results (part II). Time lag was shown to be a factor of some importance, seeming to work well with intense heat waves (long periods of high temperatures) when a considerable number of deaths continue to occur even after temperature has dropped substantially. However, the same does not happen with moderate heat. Kunst et al. (1993) showed that the highest association between heat and mortality had no time lag, becoming negative if lagged between 3 and 6 days. Since I wanted to include both extreme and moderate heat in our model I had to strike a balance (keeping the residual standard deviation at a minimum), so I opted for no time lag, which most likely underestimated intense heat waves and overestimated moderate heat. A more sophisticated approach would require that these issues be dealt separately, possibly using fuzzy logic/numbers in-between (Scherm 2000).

The model does not appear to deal properly with short-term increases in temperature, exaggerating deaths. This only occurred in the 1990s (as modelled by the1098s – see outlier in Fig. 5B for 24 July 1995) possibly because the 1980s temperature variability (measured by the standard deviation) was 0.2 °C lower than that of the 1990s (Table 4), and hence the model was calibrated to handle less variability. To overcome this problem a minimum number of days above a specific calendar threshold would have to be used, making the analysis of the data more complex. A similar event occurred in the

Table 5 Standardised (for summer) death rates from selected causes for 1998, and summer heat-related deaths analysed in this study. Rates per 100,000 population

Cause of death	Death rate
All causes	269.1
Cardiovascular diseases	107.4
Cancers	52.7
Respiratory diseases	23.9
Ischemic heart disease	23.7
Motor vehicle accidents	4.8
Summer heat-related deaths	6.2–4.9

1980s data set on 14 July 1981 (Fig. 5A), but I suspect this to be more likely due to the mortality displacement from the intense heat wave of the previous month.

I compared our results with previous studies performed in Portugal. Garcia et al. (1999) estimated 460 more deaths than expected for the district of Lisbon during the heat wave of June 1981. When used for the same days (10–20 June 1981), the two variants of the model described in this estimated between 428 and 377 deaths for the whole period. This discrepancy can be explained by the fact that Garcia et al. (1999) did not include the heat wave mortality in their calculation, so that substantially fewer deaths were expected than were observed. Furthermore, the comparison between a time-series analysis such as this one and an episode/event analysis such as that of Garcia et al. (1999) is not straightforward.

Overall this study is in line with other European studies that have looked into climate-related mortality. WISE (1999) estimated that, in Germany, a 1 °C increase of monthly summer temperature results in an increase of the corresponding death rates by 2.1%; in Italy a marginal percentage increase in summer temperature explains a 0.76% increase in summer deaths rates. Episode analysis has showed that mortality from all causes increases during heat waves in Europe. A heat wave in July–August 1995 in London, UK, was associated with 15% increase in total mortality over the 5-day period (Rooney et al. 1998). In Belgium, a heat wave in 1994 was associated with a 13.2% increase in mortality for the elderly (Sartor et al. 1995). Results for Madrid, Spain, showed an increase in mortality of up to 28.4% for every degree rise in temperature above 36.5 °C (Díaz et al. 2001). In this study, the 1981 heat wave resulted in a 107% increase of crude mortality averaged over 8 days, while the 1991 heat wave resulted in a 29% increase averaged over 10 days (both using the summer-months-mean approach).

In a national context, our estimation of a death rate of between 5.4 and 6.2 per year (in 100,000 for Lisbon) is low compared with other causes of death for Portugal (Table 5). However, one should realise that heat-related deaths are mostly from respiratory and cardiovascular diseases, which have been best correlated with heat stress (cf. Kunst et al. 1993). Unlike in the United States, very few deaths are certified as heat-related in Europe, so researchers will have to continue to use indirect methods, such as the one applied here, to quantify them. It is not necessarily appropriate, however, to apply a relationship that holds for Lisbon's population to the whole of Portugal, so even death rate comparisons at the national level must be considered with caution.

In summary, this study has shown that there have been considerable heat-related deaths in the city of Lisbon, both from moderate and extreme heat, during the summer months of 1980–1998. The empirical-statistical model constructed is shown to reproduce well the observed heat-related deaths. This makes the model more reliable for the quantification of the potential impacts of climate change on health, which is explored in part II.

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