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ENVIRONMENTAL EPIDEMIOLOGY

International study of temperature, heat and urban mortality: the 'ISOTHURM' project

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Background This study describes heat- and cold-related mortality in 12 urban populations in low- and middle-income countries, thereby extending knowledge of how diverse populations, in non-OECD countries, respond to temperature extremes.

Methods The cities were: Delhi, Monterrey, Mexico City, Chiang Mai, Bangkok, Salvador, São Paulo, Santiago, Cape Town, Ljubljana, Bucharest and Sofia. For each city, daily mortality was examined in relation to ambient temperature using autoregressive Poisson models (2- to 5-year series) adjusted for season, relative humidity, air pollution, day of week and public holidays.

Results Most cities showed a U-shaped temperature-mortality relationship, with clear evidence of increasing death rates at colder temperatures in all cities except Ljubljana, Salvador and Delhi and with increasing heat in all cities except Chiang Mai and Cape Town. Estimates of the temperature threshold below which cold-related mortality began to increase ranged from 15°C to 29°C; the threshold for heat-related deaths ranged from 16°C to 31°C. Heat thresholds were generally higher in cities with warmer climates, while cold thresholds were unrelated to climate.

Conclusions Urban populations, in diverse geographic settings, experience increases in mortality due to both high and low temperatures. The effects of heat and cold vary depending on climate and non-climate factors such as the population disease profile and age structure. Although such populations will undergo some adaptation

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to increasing temperatures, many are likely to have substantial vulnerability to climate change. Additional research is needed to elucidate vulnerability within populations.

Keywords Temperature, heat, mortality, low income populations, epidemiology, cities, meteorological factors, climate

Introduction

Studies in various cities, mostly in high-income countries, have shown that temperature extremes are accompanied by marked increases in mortality.[1–3] To date, most of the epidemiological evidence about cold- and heat-related mortality comes from Europe, Japan and North America.[4–6] For mid- to high-latitude populations, the overall effect of low temperatures predominates over that of heat. In European countries, the excess mortality in winter compared with non-winter months ranges from 10% to 28%.[7,8] However, the shape of the temperature-mortality relationships indicate a sharper rise at extremes of heat than of cold.

Globally, urbanization is proceeding at a quickening pace, with, now, over half of the world population living in cities or large towns. Most of this growth is occurring in lower-income countries, and is particularly concentrated in informal settlements and slums. This, and the prospect of higher temperatures under climate change, underscores the need to understand better how urban populations in low-income countries respond to environmental temperature.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change, published in 2007, further reinforces the evidence that we are in a phase of global climate change driven in large measure by human activity.[9] The projected increase in global mean surface air temperature by 2100 ranges from 1.8°C to 4.0°C, with that range largely reflecting uncertainties about human social-economic-technological futures. This represents a rapid pace of change, with potential environmental,[9] economic,[10] social and health consequences.[11,12] An increase in the frequency and intensity of heat waves is one of the most certain impacts of anthropogenic climate change.

In this article, we characterize systematically the patterns of temperature-related mortality in populations from 12 cities in low- and middle-income countries in order to describe current vulnerability to environmental heat and cold effects.

Methods

Study population

The 12 study cities, from five continents, were (from north to south): Ljubljana, Bucharest, Sofia, Delhi, Monterrey, Mexico City, Chiang Mai, Bangkok, Salvador, São Paulo, Santiago and Cape Town (Table 1). The cities were selected to have a wide geographical spread, and were pragmatically chosen as cities for which we were able to obtain reliable data through local contacts. The Gross National Product (GNP) per capita for the countries from which these cities were drawn ranged from US $440 to $9780 (1998 figures). For comparison, the GNP for the United Kingdom was $21 410 (1998 figure). For each city, daily counts of deaths, for periods of 2–5 years, were obtained from mortality registries with the help of local coordinators. Mortality data for Delhi and Santiago were supplied by the World Bank, which had previously assembled them for studies of air pollution and health.[13] The Delhi data relate to one of three districts in the National Capital Territory and include ~25% of the deaths in the city as a whole. There was limited information on the quality of the death registration data, but there are likely to have been problems with completeness and with certification of cause of death, particularly in the Indian and Thai cities.

Environmental variables

Daily maximum and minimum temperature, relative humidity and, where available, precipitation data were obtained from local meteorological stations. Daily mean concentrations of particulate pollution—particulate matter $<10\,\mu g/m^3$ in aerodynamic diameter (PM_{10}), black smoke (BS) or total suspended particles (TSP)—were also obtained for each city except Salvador, as well as tropospheric ozone levels, where available. Reliable data on circulating respiratory infections (such as influenza) were not available for most cities and we did not include them in our analyses.

Where data for any one city were received from two or more pollution-monitoring stations, averages were calculated. To avoid distortions due to occasional missing values in one of more stations' series, the daily measurements from each station were first standardized to zero mean and unit standard deviation. The standardized data from the various stations were then averaged by day, and the daily averages converted back to an absolute scale by multiplying by the standard deviation of the pooled data and adding the overall mean over all years. A similar procedure has been used for air pollution previously.[14] For meteorological series, a single station was used for all cities except Mexico City and Monterrey,

Table 1 Characteristics of cities

City	Latitude and longitude	Altitude (m)	Approx. population in millions	National GNP/capita in 1998[a] (US $)	Years of data	Meteorological and air pollution parameters Daily mean (5th–95th centile range): Mean temperature (°C)	Mean relative humidity (%)	Particulate concentrations[b,c] (μg/m^3)	Daily Mean number of deaths (5th–95th centile range)	Percent of deaths[d] by age-group: 0–14	15–64	65+	Percent of deaths[d] by cause: Cardio-vascular disease	Respiratory disease	Other diseases
Ljubljana	46° 03′ N	298	0.3	9780	1989–92	10.79	76.6	BS 27.1	6.7	1.2	24.4	74.5	45.6	7.3	47.1
(Slovenia)	14° 30′ E					(−2.3 to 22.8)	(56–95)	(4.7–91.0)	(3–12)						
Bucharest	44° 25′ N	80	2.3	1,360	1994–97	12.1	74.2	TSP 70.9	60.5	1.4	29.5	69.1	60.0	5.6	34.4
(Romania)	26° 07′ E					(−3.6 to 25.5)	(53–95)	(43–99.8)	(42–81)						
Sofia	42° 42′ N	550	1.4	1,220	1996–99	10.7	71.2	TSP 48.1	29.2	0.9	23.1	76.0	56.3	4.4	39.3
(Bulgaria)	23° 19′ E					(−3.3 to 23.5)	(52–89)	(3.9–126.0)	(19–41)						
Delhi[e]	28° 39′ N	239	9.9	440	1991–94	25.0	76.4	TSP 375.0	25.0	48.1	38.6	13.3	15.5	8.9	75.7
(India)	77° 13′ E					(13.5–35.2)	(56.1–93.2)	(219.5–567.5)	(14–37)						
Monterrey	25° 41′ N	538	2.5	3840	1996–99	23.2	67.3	PM_{10} 50·0	14.9	7.9	31.7	59.9	26.1	8.5	65.4
(Mexico)	100° 18′ W					(11.6–30.6)	(46–89)	(21.4–96.6)	(8–23)						
Mexico City	19° 25′ N	2240	13.6	3840	1994–98	17.2	52.6	PM_{10} 68·7	178.0	13.7	35.2	51.1	25.8	12.0	62.2
(Mexico)	99° 08′ W					(12.8–21.2)	(28.2–74.1)	(28.2–122.4)	(140–235)						
Chiang Mai	18° 47′ N	512	1.6	2160	1995–97	26.3	72.9	PM_{10} 65·3	39.2	8.0	57.1	34.9	16.9	8.2	74.5
(Thailand)	99° 00′ E					(20.7–30.4)	(46–90)	(25.1–131.4)	(29–52)						
Bangkok	13° 44′ N	12	6.6	2160	1991–92	28.9	68.9	PM_{10} 61·7	52.8	9.3	41.0	47.9	34.3	5.3	59.8
(Thailand)	100° 30′ E					(25.8–32.3)	(55.9–82.4)	(39.8–90.5)	(39–67)						
Salvador	12° 58′ S	8	2.4	4630	1996–99	26.1	81.1	–	30.6	14.0	41.2	44.9	32.4	11.8	55.8
(Brazil)	38° 30′ W					(23.3–28.7)	(72–92)		(21–41)						
São Paulo	23° 32′ S	730	9.7	4630	1991–94	20.3	78.3	PM_{10} 65·0	169.7	10.3	41.7	47.7	32.4	10.7	56.9
(Brazil)	46° 37′ W					(13.9–25.3)	(59–92.4)	(31.6–128.8)	(137–208)						
Santiago	33° 27′ S	550	5.1	4990	1998–91	16.7	71.1	PM_{10}–106·3	55.2	–	–	–	33.0	14.4	52.7
(Chile)	70° 38′ W					(8.9–24.1)	(56.0–88.0)	(50.9–219)	(39–77)						
Cape Town	33° 55′ S	8	2.7	3310	1996–99	18.9	70.9	PM_{10} 26·2	39.8	10.9	42.0	47.0	32.2	11.6	56.1
(S. Africa)	18° 26′ E					(10.9–23.5)	(51.3–87.3)	(13.1–49.1)	(25–58)						

[a] *Source*: World Bank, World Development Indicators 2000.
[b] BS, Black smoke; PM_{10}, particulate matter $<10\,\mu g/m^3$; TSP, total suspended particles.
[c] Pollution measures were based on data from nine monitoring stations in Delhi, five in Monterrey and Mexico City, three in Bangkok and two in Chiang Mai, Santiago and Cape Town.
[d] All-cause deaths excluding external causes. Causes of death were based on the classifications used by the local data bases (ICD codes were not always given), age-specific mortality data not available for Santiago.
[e] Deaths for Delhi relate to one of three districts in the National Capitol Territory, and include ~25% of total for the city.

where data were provided as a daily average value from all reporting monitors.[15]

Missing data for daily particulate concentrations were imputed (on the logged scale) using linear regression models. These models used as explanatory variables day of week, week of year, year and public holiday, and (where available and statistically significant) minimum and maximum daily temperature, relative humidity, other pollution measures (sulphur dioxide, nitrogen dioxide, ozone), wind speed, wind direction and rainfall. Missing values of temperature or relative humidity were present only in Delhi (71 days) and Salvador (2 days, omitted from analyses). In Delhi, we imputed missing relative humidity as the mean of the previous and next day's value, where available, and estimated the 2-day and 14-day means of temperature from at least one and at least 7 days data, respectively.

Statistical approach

Our general approach was to first describe graphically the temperature and mortality relationships in each city. We then quantified this association for each city, separately for heat and cold, assuming a linear response above and below a threshold temperature, respectively.

Natural cubic splines (cubic splines constrained to be linear beyond the data range) were also used to create graphs of the temperature-mortality relationship, where mortality is plotted as smoothed functions of temperature, with 1 df (degrees of freedom) for every 5°C range in temperature.

Analyses were based on deaths from all causes, excluding deaths from external causes (i.e. excluding ICD-9 codes above 800 or the equivalent classification). For each city, daily mortality was examined in relation to ambient temperature using Poisson generalized linear models adjusted for autocorrelation (order 3), similar to models used for studies of air pollution and health.[16,17] The temperature parameter used in the models was daily mean temperature as it had slight predictive advantage over daily minimum and daily maximum temperature. Daily relative humidity, day of week, public holidays and daily particulate pollution concentrations (mean of index and previous day) were also included in the models. Particulate concentrations were included because of consistent reports of association with daily mortality in studies around the world,[18] and public holidays because patterns of mortality and behaviour influencing exposure to ambient conditions may change on these days. Data on ambient ozone levels, available only for a subset of cities, were not included in the main analyses because of their dependence on temperature and sunlight (thus placing ozone—at least in part—on the causal pathway between temperature and mortality). However, for cities with reliable ozone data, we also ran models including ozone to test its influence on the reported temperature effects.

We fitted cubic smoothing splines of date with equally spaced knots to control for secular trends (e.g. demographic shifts) in mortality and additional confounding by seasonally varying factors other than temperature. We used 7 df/year for these smoothing splines (roughly equivalent to a 2-month moving average). This number of df was chosen as a compromise between providing adequate control for unmeasured confounders and leaving sufficient information from which to estimate temperature effects in the short-term.[19] To test whether the choice of number of df was critical to the results, we carried out sensitivity analyses using 3 and 10 df/year and using no seasonal adjustment at all.

Plots of partial autocorrelation functions of residuals indicated moderate positive autocorrelations of low order, rarely above three. Therefore, we incorporated autocorrelation into the model as lagged residuals of the model without autocorrelation[20] although this strategy had little influence on the results.

We used models that allowed the effects of heat and cold to be distributed over a number of days as suggested by the results of our own exploratory analyses and the evidence of other published research.[6,19,21] Specifically, to best identify heat effects, which are mainly related to recent high temperatures, we fitted spline models of the average of daily mean temperatures over the index and previous day. In a separate analysis to best identify cold effects, which are generally more delayed, we fitted models of the average of mean daily temperature over the index day and the previous 13 days.

To quantify the adverse effects of low and high temperatures simply, we used 'hockey stick' (linear spline) models—i.e. models that assume a log-linear increase in risk below a cold threshold (t_l°C) and above a heat threshold (t_h°C). Specifically, for low temperature effects, mortality was assumed to increase as a log-linear function of the mean over the previous 14 days of daily temperature deficits below a low threshold t_l. High temperature effects were assumed to be log-linear functions of 2-day mean temperature exceedances over a high threshold t_h. The high and low temperature terms were fitted simultaneously.

The heat and cold thresholds (t_l and t_h) were estimated separately for each city using maximum likelihood, that is, by the calculation of likelihoods over all integer values for thresholds in the range of the data, constrained for interpretability so that $t_l = t_h$ where unconstrained estimates gave $t_l > t_h$. Likelihood profile CIs were calculated from arrays of likelihoods with adjustment for over-dispersion. CIs for the slopes are those which apply given the estimated thresholds of cold and heat effects—i.e. they do not reflect uncertainty in the threshold estimates. All analyses used STATA.

For clarity of presentation, we show the results of analyses for all ages and all-cause mortality, together with comparison of reported cardiorespiratory and non-cardiorespiratory cause-of-death groups. Plots of temperature-mortality relationships for some specific cause-of-death groups are provided as supplementary material.

We investigated whether heat and cold thresholds are related to average temperatures, as an indication of adaptation to local climate.[6] We did this by graphing the thresholds against annual mean and maximum temperatures. In addition, we applied a random effects meta-regression to the coefficients of temperature-related mortality and a number of other city-level characteristics to explain possible heterogeneity.[22]

Results

Seasonal patterns of weather and mortality

Seasonal (intra-annual) variation in all-cause mortality, mean daily temperature and rainfall is shown by city in Figure 1. Overall, cities with comparatively cool minimum temperatures and large temperature fluctuations also had large seasonal fluctuations in mortality, with the highest rates of death occurring during periods of relative cold. This was not, however, true for Delhi where death rates were low during the coolest periods of the year and highest in the third quarter—at or just after the monsoon. Of the four cities in the tropics (within 23° 27′ north or south of the equator), three—Bangkok, Chiang Mai and Salvador—showed only modest variation in mortality across the year, while high altitude Mexico City (19° N, 2240 m above sea level) showed much clearer seasonality. The two Mexican cities were notable for the sharpness of the rise and fall in mortality in the months around mid-winter—despite there being only a modest winter dip in temperatures in these cities. In contrast to the broadly observed association between cold periods and mortality, no seasonal increase in death rates was clearly discernible from these graphs during periods of highest temperature.

Temperature mortality plots

The graphs of Figure 2a show smoothed plots of mortality against the mean of the current and previous day's temperature. The curves are the fitted values of the fully adjusted models with 1df for every 5°C. The graphs reveal a wide variety of non-linear temperature-mortality relationships, though in every city except Chiang Mai and Cape Town an increase in mortality with increasing temperature was evident over part of the temperature distribution.

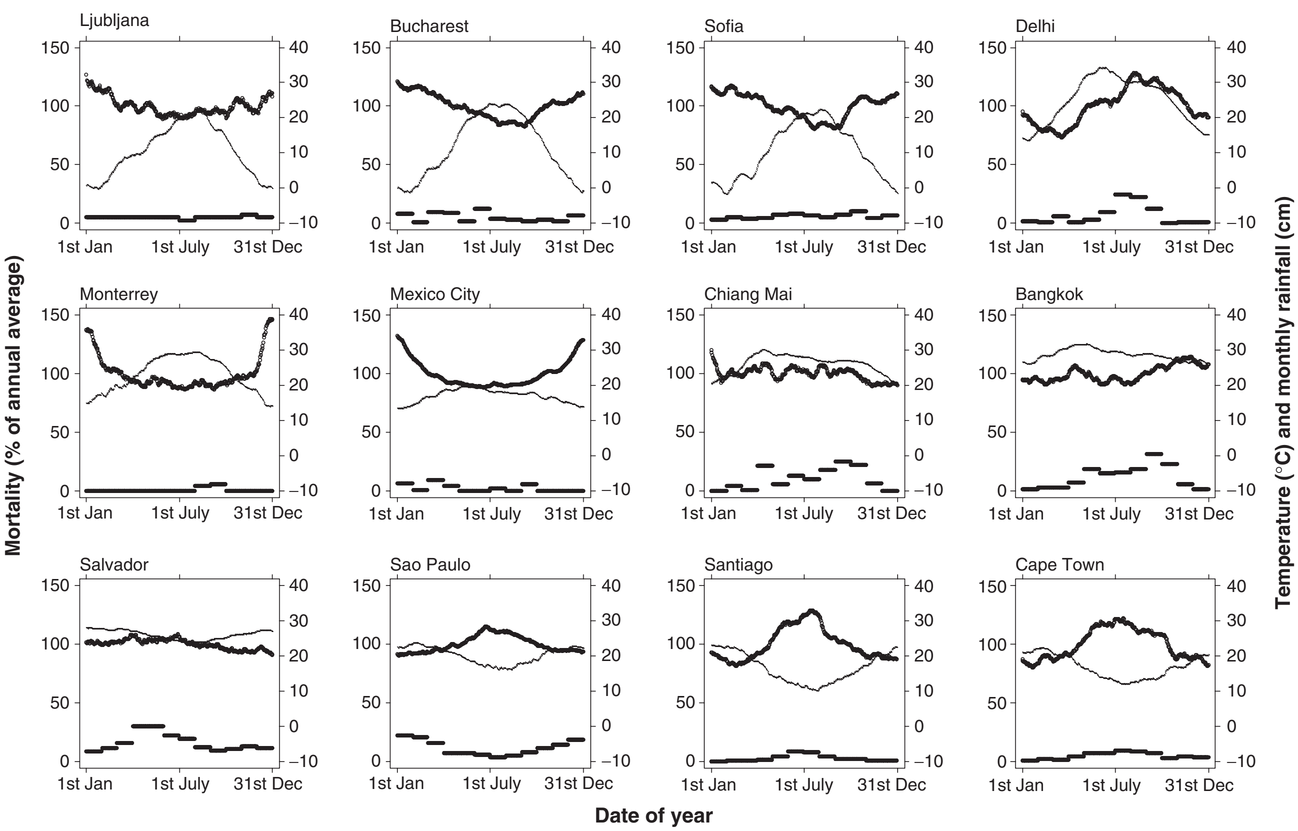

Figure 1 Average seasonal pattern of daily mortality (upper bold lines), and daily temperature and monthly rainfall (lower curves). Data for all years averaged by day of the year. Daily mortality (the *Y*-axis) is expressed relative to the annual average mortality for that city, as a percentage

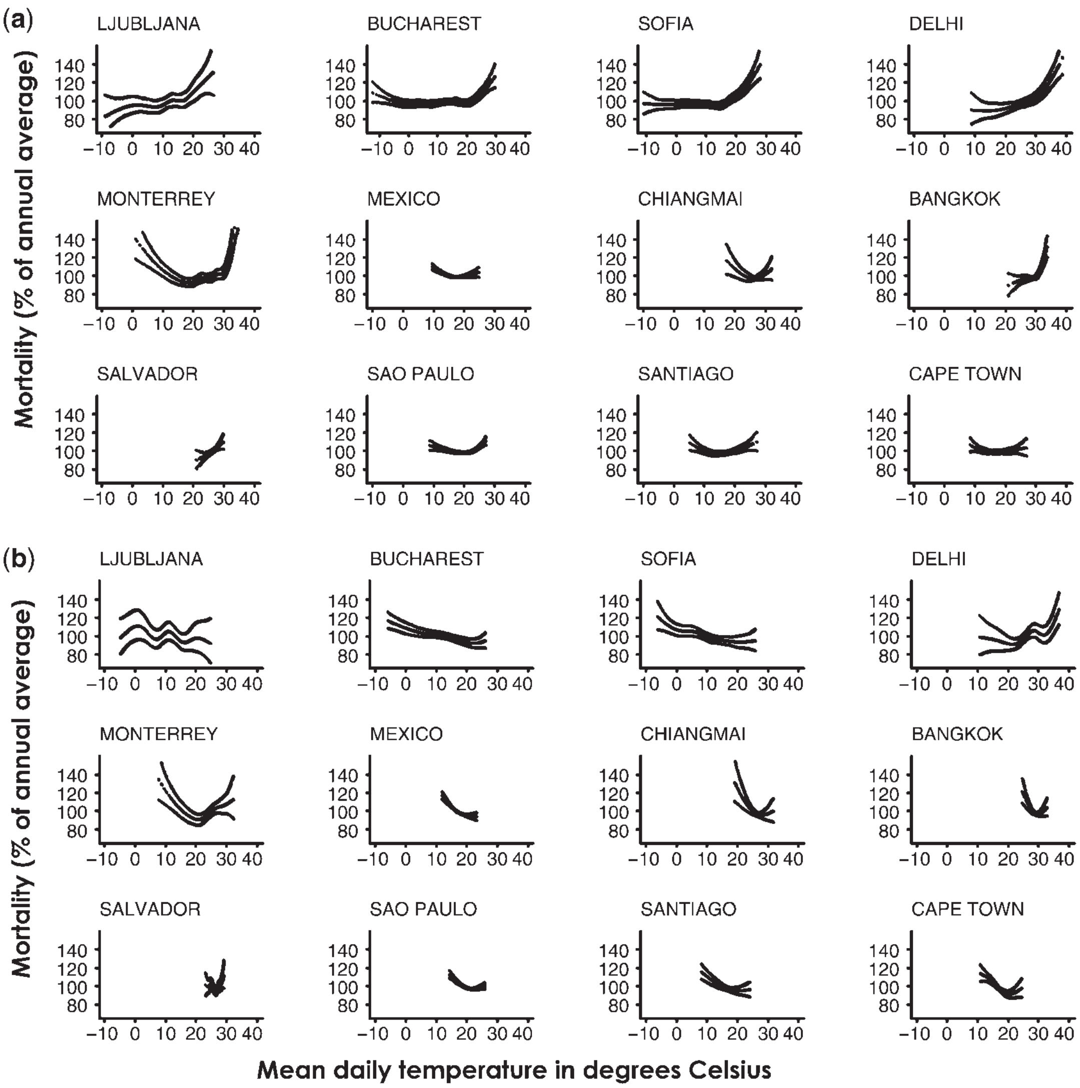

Figure 2 Natural cubic spline regression curves for daily mortality on (**a**) the mean temperature over the current and previous days (lags 0 and 1); (**b**) the mean temperature over the current and previous 13 days (lags 0–13). Each figure shows the spline curve (the middle line) with a 95% CI (the outer two lines). The curves are adjusted for smooth temporal variation, relative humidity, day-of-week, public holidays and particulate pollution as described in the text. Predicted mortality (the *Y*-axis) is expressed relative to the annual average mortality for that city, as a percentage

Particularly, large heat-related fluctuations in mortality were apparent in Monterrey, Delhi, Bangkok and Sofia, though the shape of the curves and the threshold for heat effects varied. For Salvador and Delhi there was a positive association between temperature and mortality throughout the temperature range of those cities.

Figure 2b contains smoothed plots of mortality against the mean of temperature over the index day and preceding 13 days. Again the patterns vary. These curves show clear evidence of cold-related deaths in all cities except Ljubljana, Salvador and Delhi. A cold effect over the entire, or almost the entire, temperature distribution was seen in Bucharest, Sofia and Mexico City. Particularly steep cold gradients were seen over part of the temperature distribution in Chiang Mai, Monterrey, Mexico City and Bangkok. The gradients were comparatively shallow in Bucharest and Sofia, but the cold effects occurred over much wider temperature ranges. In contrast, mortality varied little across the narrow range of temperatures in Salvador.

Additional graphs by cause of death (available on request from the authors) suggest that heat contributes to cardiovascular disease mortality in most cities. Cold-related cardiovascular deaths were seen in each of the European cities, Mexico City, Bangkok, São Paulo, Santiago and Cape Town. Respiratory disease mortality increased with heat in Bucharest, Sofia, Salvador and São Paulo, and with cold in Mexico City, São Paulo, Santiago and Cape Town, although several curves did not allow clear interpretation.

Deaths from 'other causes' accounted for more than half of all deaths in the non-European cities and included non-specific or unclassified causes of deaths (Table 1). The graphs were, therefore, mostly very similar to those for all-cause mortality. The main difference was that in Santiago deaths from 'other causes' did not show evidence of being cold-related.

With regard to age, the patterns of temperature-related all-cause mortality in the adult (15–64 years) and elderly (65+ years) populations were very similar to the all-ages graphs of Figure 2. Relatively small numbers of deaths meant that graphs for children were often imprecise.

Quantification of temperature-mortality relationships

To provide quantitative estimates of temperature-mortality relationships we show in Table 2 the results of the 'hockey-stick' models in which heat and cold effects were assumed to follow simple linear forms above and below the threshold temperatures. Thus, for each city, we obtained a slope and threshold for the cold relation with mortality using the 2-week mean temperature, and simultaneously a separate slope and threshold for the heat relation using the 2-day temperature means.

Point estimates of the temperature threshold below which cold-related mortality first occurred ranged from 15°C to 29°C. The threshold above which heat-related deaths occurred ranged from 16°C to 31°C. The increase in mortality per °C fall in temperature below the cold threshold was greatest in Chiang Mai, Mexico City, Monterrey and Bangkok. The increase in mortality per °C above the heat threshold was greatest in Monterrey, Bangkok, Delhi and São Paulo. However, both cold- and heat-related gradients in mortality were sensitive to the selection of the threshold, making comparison difficult. The very large gradients for cold in Chiang Mai and for heat in Monterrey in part reflect the fact that the corresponding thresholds were very close to the edge of the observed temperature distributions in these cities.

These models all included particulate air pollution, but the impact of its inclusion on the temperature slopes was very small (<20% proportional change in the coefficient) for all except two small and imprecisely estimated terms: the Ljubljana cold slope (which reduced from 0.43%/°C to 0.23%/°C if PM was removed), and the Cape Town heat slope (0.47 to 0.67%).

Thresholds and slopes for cardiorespiratory and non-cardiorespiratory causes-of-death

To explore hockey stick models for specific causes of death, we classified mortality into cardiorespiratory and non-cardiorespiratory disease (Table 3). Even with this fairly broad subdivision across all ages, a number of thresholds and slopes are imprecise. In several cases (the blank cells of Table 3), there was no clear evidence of a threshold for heat or cold effect. In several other cases, the array of likelihoods for temperature thresholds (which were particularly ill-defined for non-cardiorespiratory disease) suggested values of t_l and t_h very close to the edge of the temperature distributions (e.g. with cold thresholds below the 5th centile

Table 2 Threshold and slopes of temperature-mortality relationships

City	Threshold (°C) with 95% CI: Lower (cold[a])	Threshold (°C) with 95% CI: Upper (heat[b])	Percentage increase in mortality for each °C decrease in temperature below 'cold threshold' (95% CI)[c]	Percentage increase in mortality for each °C increase in temperature above 'heat threshold' (95% CI)[c]
Ljubljana	17 (7–20)	17 (7–20)	0.43 (−0.78 to 1.65)	3.12 (1.26–5.02)
Bucharest	22 (20–22)	22 (20–22)	0.85 (0.44–1.25)	3.30 (2.35–4.26)
Sofia	16 (15–17)	16 (15–17)	0.93 (0.37–1.49)	2.88 (2.11–3.65)
Delhi	19 (.–39)[d]	29 (8–30)	2.78 (0.66–4.94)	3.94 (2.80–5.08)
Monterrey	17 (13–19)	31 (31–33)	4.70 (3.04–6.40)	18.8 (13.0–25.0)[e]
Mexico City	15 (14–15)	18 (8–21)	6.90 (5.70–8.11)	0.77 (0.14–1.39)
Chiang Mai	19 (.–20)[d]	28 (17–.)[d]	84.3 (48.1–129)[e]	2.39 (−0.49 to 5.35)
Bangkok	29 (29–30)	29 (29–30)	4.09 (1.27–6.98)	5.78 (3.52–8.09)
Salvador	23 (.–30)[d]	23 (20–27)	−12.8 (−34.7 to 16.4)	2.48 (0.93–4.05)
São Paulo	21 (18–22)	23 (19–23)	2.47 (1.78–3.16)	3.46 (2.62–4.31)
Santiago	16 (14–20)	16 (14–20)	2.53 (1.44–3.62)	1.04 (0.28–1.81)
Cape Town	17 (15–22)	17 (15–22)	3.82 (2.08–5.60)	0.47 (−0.31 to 1.24)

[a]Lower and
[b]Upper change points of linear spline hockey stick models (constrained so that $t_l \leqslant t_h$).
[c]Adjusted for particle air pollution, relative humidity, day of week, public holidays, season.
[d]CI extends to limit of observed temperature range.
[e]Cold threshold below the 5th centile of the observed temperature distribution or heat threshold above 95th centile.

Table 3 Comparison of thresholds and slopes for cardiorespiratory and non-cardiorespiratory causes of death

City	Cause of death	5th and 95th centiles of temperature distribution	Threshold in °C (95% CI)[a] Lower (cold)	Upper (heat)	Percentage increase in mortality for each °C below 'cold threshold' (95% CI)[b]	Percentage increase in mortality for each °C above 'heat threshold' (95% CI)[b]
Ljubljana	Cardioresp	−2.3, 22.8	–	18 (15–21)	–	3.35 (0.43–6.35)
	Non-cardioresp	−2.3, 22.8	–	−10 (−11 to 17)	–	1.77 (0.67–2.88)
Bucharest	Cardioresp	−3.6, 25.5	−7 (−8 to 22)	22 (21–23)	21.2 (10.9–32.5)	3.92 (2.75–5.10)
	Non-cardioresp	−3.6, 25.5	–	20 (16–23)	–	1.87 (0.76–3.00)
Sofia	Cardioresp	−3.3, 23.5	−3 (−9 to 1)	15 (14–17)	6.28 (2.60–10.1)	3.43 (2.47–4.39)
	Non-cardioresp	−3.3, 23.5	21 (9–28)	28 (15–.)[c]	1.15 (0.33–1.97)	510 (118 to >1000)[d]
Delhi	Cardioresp	13.5, 35.2	12 (.–13)[c]	17 (12–19)	203 (41.2–553)[d]	3.94 (2.38–5.53)
	Non-cardioresp	13.5, 35.2	19 (.–30)[c]	30 (27–31)	2.65 (0.21–5.16)	4.30 (2.89–5.72)
Monterrey	Cardioresp	11.6, 30.6	17 (13–20)	30 (30–31)	5.36 (2.49–8.31)	17.6 (11.0–24.7)
	Non-cardioresp	11.6, 30.6	17 (10–19)	33 (18–33)	4.58 (2.58–6.61)	49.3 (27.8–74.3)[d]
Mexico City	Cardioresp	12.8, 21.2	15 (15–16)	16 (15–20)	9.18 (7.31–11.09)	1.05 (0.36–1.75)
	Non-cardioresp	12.8, 21.2	14 (13–15)	21 (14–.)[c]	8.21 (5.98–10.48)	1.53 (−0.57 to 3.67)
Chiangmai	Cardioresp	20.7, 30.4	–	–	–	–
	Non-cardioresp	20.7, 30.4	19 (.–20)[c]	–	98.8 (56.1–153)[d]	–
Bangkok	Cardioresp	25.8, 32.3	–	–	–	–
	Non-cardioresp	25.8, 32.3	29 (26–30)	29 (28–30)	4.46 (0.89–8.17)	7.52 (4.62–10.5)
Salvador	Cardio–resp	23.3, 28.7	–	28 (27–28)	–	14.7 (4.69–25.7)
	Non-cardioresp	23.3, 28.7	–	22 (21–25)	–	2.61 (0.66–4.59)
São Paulo	Cardioresp	13.9, 25.3	21 (18–23)	23 (23–24)	3.35 (2.38–4.32)	3.26 (2.04–4.50)
	Non-cardioresp	13.9, 25.3	19 (17–21)	19 (18–21)	2.75 (1.51–4.01)	1.68 (1.21–2.15)
Santiago	Cardioresp	8.9, 24.1	17 (15–19)	17 (15–26)	5.03 (3.60–6.49)	1.47 (0.25–2.72)
	Non-cardioresp	8.9, 24.1	–	–	–	–
Cape Town	Cardioresp	10.9, 23.5	18 (.–26)[c]	–	2.70 (0.44–5.01)	–
	Non-cardioresp	10.9, 23.5	16 (15–22)	–	5.29 (2.60–8.05)	–

Slopes not shown where there was no evidence of heat or cold threshold.
[a]Thresholds constrained so that low threshold ⩽ high threshold.
[b]Adjusted for particle air pollution, relative humidity, day of week, public holidays, season
[c]Dot (.) for boundary of CI indicates a boundary close to but within limit of observed temperature range.
[d]Cold threshold below the 5th centile of the observed temperature distribution or heat threshold above the 95th centile.

or heat thresholds above the 95th centile, respectively). In these cases, the associated temperature-mortality slope often was of large magnitude, reflecting the instability of the slope estimates when data are sparse over a very narrow temperature range.

Overall, the results confirm a broadly U-shaped temperature-mortality relation for both cause-of-death groups, although the evidence was less consistent for non-cardiorespiratory diseases. Where the thresholds were not towards the extremes of the temperature distributions, the results showed a fairly consistent pattern, with a several per cent increase in cardiorespiratory mortality for each degree temperature decrease below the cold threshold or increase above the heat threshold. For non-cardiorespiratory diseases the slopes were more variable, possibly reflecting the greater variation between cities in the component causes of death. Some apparently surprising results (such as the 'heat' threshold of −10°C for Ljubljana) can probably be discounted as sampling errors (95% CI of −11 to 17).

Second stage meta-regression models

Heat thresholds were generally highest in cities with high annual mean temperatures (P-value for trend = 0.005), and there was suggestive evidence that cold thresholds tended to be lowest in cities with low annual mean temperatures (P-value for trend = 0.06) (Figure 3). In addition, we observed a slight negative

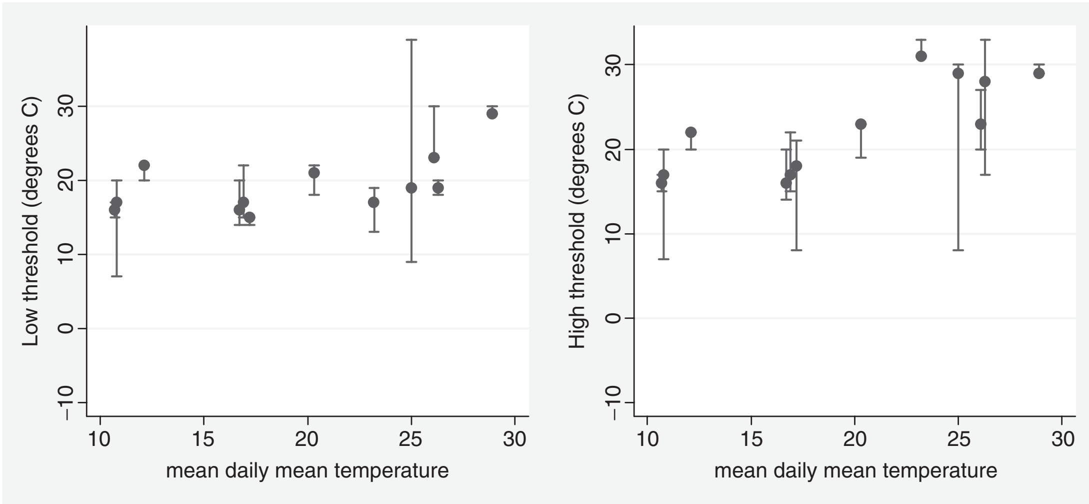

Figure 3 Temperature thresholds against annual mean temperatures for the 12 cities. (Vertical bars indicate 95% CI.)

association between cold slopes and annual relative humidity. Apart from these associations, the random effects second stage regression models revealed no associations significant at $P < 0.05$ between either the heat/cold thresholds or slopes and any of the following variables from Table 1: latitude, altitude, GNP, annual mean temperature, annual mean relative humidity or proportion of deaths in 65+ age group.

Discussion

This is the first systematic attempt to characterize and compare temperature-mortality relationships in low- and middle-income cities using consistent methods. The cities studied cover a broad range of latitude, average seasonal temperature and economic development.

In interpreting our results, we note first that the precise forms of the temperature-mortality relationships depend to some degree on the statistical methods used to derive them—for example, the method of adjustment for unmeasured seasonal influences and the lag structures used.[19] For the hockey stick models, the slopes depend on the temperature thresholds which, as their CIs suggest, are not determined with precision. We attempted, however, to construct models that reflect the underlying temperature-mortality associations as accurately as possible, and we tested the sensitivity of the results to a number of methodological choices. We also used an approach that had sufficient flexibility to characterize very different temperature-mortality patterns (variable df for the mortality graphs depending on the temperature range, separate thresholds), while using some common methods (e.g. identical df for seasonal smoothing) to aid comparability between cities. The lack of reliable data on seasonal respiratory infections for most cities was only a minor limitation for estimating cold-related mortality, given the inclusion of adjustment for seasonal factors by use of cubic smoothing splines,[15,23] and that lack is unlikely to influence heat effects. Although we adjusted for particle air pollution,[15] we considered it inappropriate also to adjust for ozone levels which are, in part, a function of temperature and sunlight. We adjusted for ozone in seven cities (Sofia, Monterrey, Mexico City, Chiang Mai, São Paulo, Santiago and Cape Town) as a sensitivity analysis, but the resultant effect on heat slopes was small (mostly identical or very similar to two significant figures—data available from the authors on request).

For all-cause mortality there were important differences between cities, with some evidence of cold-related increases in mortality in all cities except Ljubljana and Salvador, and of heat-related increases in all cities except Chiang Mai and Cape Town. When the modelled thresholds for heat and cold effects were towards the upper and lower limits of the temperature distribution for the relevant city, the slopes from the hockey stick models were sometimes less stable. But, if interpreted in combination with the plots of Figure 2, the results show that steep increases in mortality with high and low temperatures occurred over part of the temperature distribution in cities from both tropical and temperate regions. Monterrey displayed a particularly impressive increase in mortality at both lower and upper ends of the observed temperature range.

The differences between cities were not explained by the demographic or economic factors we explored in the meta-regression. The small number of cities in this assessment (12) limits the power of a second stage analysis to reveal explanatory factors for the observed variation in population response patterns to environmental temperatures. Effective preventive ('adaptive') policies will require understanding of the particular demographic, social and ecological determinants, and sensitivities, of the response pattern of the population of concern. Relevant determinants include the population's age structure, socio-economic profile, prevalence of temperature-sensitive diseases, public understanding of the hazards to health, the built environment and level of infrastructure development and public health services, including the presence of heat or cold health protection measures, such as heat-health warning systems.

Populations adapt to their local climate—physiologically, culturally and behaviourally. In mid-latitude populations, the steepness of the relationship between cold temperatures and mortality was inversely related to the average winter temperature.[7] It is unclear whether, within Europe, there is an important difference between warmer and cooler cities in the burden of heat-related deaths.[24] In high-income countries, the sensitivity of mortality to cold[25,26] and to heat[27–29] has declined in recent decades. The evidence from the Paris heat-wave in August 2003, however, showed the potential impact, even in a high-income country, when the population is exposed to an unaccustomed intensity and duration of heat.[1]

The public health importance of heat-[30] and cold-related mortality[31] is currently receiving more attention within Europe and North America. The extent to which heat effects are due to the bringing forward of death by just a few days or weeks (short-term mortality displacement) is still uncertain. For cold, the impacts on mortality appear to accumulate over a longer time course, and there is no clear evidence of short-term mortality displacement.[21] It is not possible to quantify years of life lost from time-series studies, but there is good evidence that, in general, short-term mortality displacement does contribute to the excess of deaths attributed to heat,[32,33] while the overall excess will depend on characteristics of each particular population.[34] On pathophysiological grounds, it is unlikely that short-term mortality displacement would account for all or most temperature-related infectious disease mortality or acute events (heart attacks, strokes) at older ages. The limited evidence available indicates that short-term displacement does not account substantially for heat-related deaths in low-income populations.

The patterns of temperature-related mortality we observed are influenced by both climate and non-climate factors. In the future, populations may become less sensitive to heat effects due to economic development, although unplanned rapid development can have adverse effects on sanitation, air pollution and housing, that may add to future vulnerability.[35] Our study suggests that populations in many cities in low- and middle-income countries are likely to have substantial vulnerability to the direct impacts of climate change on extremes of temperature. More extended research is needed to improve understanding of the modulating roles of such factors as housing quality, technology, local topography, urban design and behavioural factors, and to improve assessment of adaptive capacity to current and future climates.

Supplementary material

Supplementary data are available at *IJE* Online.

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KEY MESSAGES

- In cities with temperate, tropical and subtropical climates, temperature was associated with daily mortality, with increased mortality risk at both high and low extremes of the temperature distribution in most cities.
- A higher heat threshold (the temperature above which mortality risk clearly begins to increase) was seen in cities with hotter summers, reflecting the adaptation of the population.
- Other differences in temperature and mortality associations (slopes and thresholds) were not related to the several climate, socio-economic and demographic factors that we explored.
- Populations in cities in low- and middle-income countries are adversely affected by high temperatures and may be especially vulnerable in future to the direct impacts of more extreme temperatures under climate change.

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