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Vulnerability to heat-related mortality in Latin America: a case-crossover study in São Paulo, Brazil, Santiago, Chile and Mexico City, Mexico

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Background Factors affecting vulnerability to heat-related mortality are not well understood. Identifying susceptible populations is of particular importance given anticipated rising temperatures from climatic change.

Methods We investigated heat-related mortality for three Latin American cities (Mexico City, Mexico; São Paulo, Brazil; Santiago, Chile) using a case-crossover approach for 754 291 deaths from 1998 to 2002. We considered lagged exposures, confounding by air pollution, cause of death and susceptibilities by educational attainment, age and sex.

Results Same and previous day apparent temperature were most strongly associated with mortality risk. Effect estimates remained positive though lowered after adjustment for ozone or PM_{10}. Susceptibility increased with age in all cities. The increase in mortality risk for those $\geqslant$65 comparing the 95th and 75th percentiles of same-day apparent temperature was 2.69% (95% CI: −2.06 to 7.88%) for Santiago, 6.51% (95% CI: 3.57–9.52%) for São Paulo and 3.22% (95% CI: 0.93–5.57%) for Mexico City. Patterns of vulnerability by education and sex differed across communities. Effect estimates were higher for women than men in Mexico City, and higher for men elsewhere, although results by sex were not appreciably different for any city. In São Paulo, those with less education were more susceptible, whereas no distinct patterns by education were observed in the other cities.

Conclusions Elevated temperatures are associated with mortality risk in these Latin American cities, with the strongest associations in São Paulo, the hottest city. The elderly are an important population for targeted prevention measures, but vulnerability by sex and education differed by city.

Keywords Brazil, cause of death, Chile, education, heat, Latin America, Mexico, mortality, sex, socioeconomic status, temperature

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Introduction

Numerous studies have investigated heat-related mortality, generally finding elevated mortality at higher temperatures.[1] Several studies indicate that some segments of the population may be more susceptible to extreme temperature than others. This susceptibility or vulnerability (we use the terms interchangeably here[2]) may result from disproportionate exposure; underlying medical or biological factors related to age, sex or disease status and/or access to other amenities (nutritious food, adequate water, proper health care) that may increase resilience during hot weather. Differences in population susceptibility are of particular interest with increasing evidence that climate change contributes to increased frequency, intensity and duration of heat waves,[3] and that climate change will affect the most disadvantaged populations, amplifying social disparities in health, both within and between countries.[4]

Weather and mortality research suggests that a wide array of characteristics may affect susceptibility to heat, including socio-economic factors, measured at both the individual and area level.[5–7] Age and sex may also play a role with women and the elderly at most risk.[6–8] Other factors indicated to modify weather-mortality relationships include race,[5,6,9–11] air conditioning prevalence,[11] widow status,[7] previous psychiatric condition,[7] residence in nursing home,[7] level of urbanization or cost of living[12] and diabetes.[9,10] Those living on a high floor of high-rise buildings, infants and persons with pre-existing cardiovascular or respiratory disease may also be at higher risk.[1]

To date, the impact of heat on mortality has been researched most extensively in the United States[5,6,10,13–17] and Europe[7,18–22] with other studies in South Africa,[23] Japan[24] and Canada.[12,25] Only a limited number of studies examined this topic for Latin America.[26–31] The present study examines vulnerability to heat-related mortality for three Latin American cities: São Paulo, Brazil; Santiago, Chile and Mexico City, Mexico. We applied a case-crossover approach to estimate city-specific non-linear exposure–response relationships for weather and total, cardiovascular and respiratory mortality risk. We investigated the lag structure of exposure and susceptibility to heat-related mortality by sex, age and educational attainment.

Materials and methods

Weather, pollution and mortality data

For each city, daily data were obtained for 1998–2002 for weather (temperature, humidity) and pollution [particulate matter with aerodynamic diameter $<10\,\mu$, PM_{10}, in $\mu g/m^3$, daily 8 h maximum ozone (O_3) in ppb]. Pollution variables were acquired from four monitors in Mexico City, seven in São Paulo and eight in Santiago. As in previous studies, the Xalostoc station in Mexico City was excluded because it is sited near industry and does not correlate well with other monitors.[32] Weather variables were obtained from three monitors in São Paulo, three in Santiago and eight in Mexico City. Daily city-wide weather and pollution levels were calculated by averaging monitor values within each city. Weather data were converted to daily mean apparent temperature, a construct intended to reflect the physiological experience of combined exposure to humidity and temperature and thereby better capture the response on health than temperature alone.[33] The metric of apparent temperature has been applied in previous studies of weather and mortality.[7,8,12,29]

Individual mortality data were obtained from São Paulo's Mortality Information Improvement Program (PRO-AIM), Chilean National Institute of Statistics (INE) and Mexican National Institute of Statistics, Geography and Information (INEGI). Data were originally collected from death certificates, which include date and cause of death, age, sex and educational attainment. Age was categorized as 0–15, 16–64 or $\geqslant 65$ years, or missing. Educational attainment was assessed for those $\geqslant 21$ years as none, primary, secondary, university degree or missing. Due to variation in educational categories and coding systems by city, educational attainment could not be identically classified across cities. Primary education corresponds to 1–6 years in Mexico City and Santiago and 1–7 years in São Paulo. Secondary education corresponds to 7–11 years in Mexico City and Santiago and 8–11 years in São Paulo.

Cause of death included all non-accidental mortality, which excluded International Classification of Diseases 10th Revision (ICD 10) Codes S and above; respiratory mortality (ICD 10 Chapter J 100–118, 120–189, 209–499 and 690–700); and cardiovascular mortality (ICD 10, Chapter I <800). Data for December 31, 2002 was omitted for analysis of Mexico City as administrative irregularities resulted in an unusually low mortality count on this day (55 deaths compared with an average 188.2 deaths/day on other days).

Case-crossover analysis

In case-crossover design, each death is a 'case' and each individual acts as his or her own control. This method was initially developed to avoid selection bias in controls for study of triggers of myocardial infarction,[34,35] and has since been applied to mortality risk related to air pollution[36–38] and temperature.[39,40] Exposure to apparent temperature at the case period (i.e. day of death) is compared with exposure at the control period (i.e. referent periods before or after the event). We applied conditional logistic regression and allowed non-linear relationships between weather and mortality using a natural cubic spline of mean apparent temperature with 3 degrees of freedom. Analyses were performed in SAS 9.1.3 and R 2.4.1.

We used a time-stratified approach to select referent periods, which prevents bias introduced by alternative control selection methods.[41] Controls were defined as all days within a given month and year with the same day-of-the-week as the case period, thus controlling for season by design. Ozone and PM_{10} were evaluated as potential confounders by including variables for each pollutant in the model. Lags for pollution adjustment were determined by first modelling weather and pollution for each lag structure for ozone and PM_{10} separately, considering single day lags of 0 days (same day), 1 day (previous day) or 2 days (2 days previous), in each community for total mortality and selecting the lag with the strongest effect (i.e., highest point estimate, smallest variance) for that pollutant and community. For apparent temperature, single day lags of 0–3 days were applied, as well as cumulative lags up to the previous week (lags 0 through 6) using a moving average. We also investigated multiple susceptibilities by stratification (e.g. effect of education on heat-related mortality within the older age group).

We present results based on the change in mortality risk for given percentiles of the city's own temperature distribution. This accounts for differences in effects for a specific temperature, which vary by the city's climate. In other words, what constitutes a hot day in one city with respect to health may be a moderate temperature elsewhere. Similar approaches based on relative temperatures were applied elsewhere.[10,29] City-specific results are presented for this non-linear relationship as well as the odds ratio of mortality risk at the 95th percentile of apparent temperature compared with the 75th percentile, based on city-specific weather distributions.

Table 1 Pollution, weather and mortality in three Latin American cities (1998–2002)

Study period	Santiago January 1, 1998 to December 31, 2002	São Paulo January 1, 1998 to December 31, 2002	Mexico city January 1, 1998 to December 30, 2002
Weather and pollution Mean (interquartile range)			
Apparent Temperature (°C)	13.5 (8.1)	21.2 (7.0)	14.4 (3.7)
PM_{10} ($\mu g/m^3$)	78.7 (37.6)	48.9 (26.0)	53.8 (34.3)
Ozone (ppb)	68.3 (51.4)	61.2 (38.5)	72.4 (35.0)
Population characteristics (%)			
Sex			
Male	51.1	53.1	50.1
Female	48.9	46.9	49.9
Educational attainment at death (for those ⩾21 years)			
None	4.9	11.0	17.4
Primary	57.5	44.6	28.5
Secondary	12.4	10.1	44.3
University	25.1	6.9	8.0
Unknown	0.2	27.4	1.8
Age at death			
0–15 years	4.0	10.9	11.3
16–64 years	29.0	35.9	35.0
65 years	67.0	52.7	53.7
Unknown	0	0.4	0.04
Cause of death (%)			
Cardiovascular	27.5	36.3	25.7
Respiratory	6.7	5.6	3.4
Other non-accidental	65.8	58.1	70.9
Total number of observations	123 694	287 044	343 553

Results

Table 1 summarizes pollution, weather and mortality statistics by city. Six days in São Paulo were missing weather data. No other cities had missing weather data, and no community had missing pollution data. A total of 754 291 deaths were included. The cities differ in age distribution at death, with higher life expectancies in Santiago. Other differences among cities include higher temperatures for São Paulo and higher PM_{10} levels and educational attainment for Santiago. In all cities, more deaths were attributed to cardiovascular than respiratory causes. Correlations between weather and pollution variables are provided in Supplementary Table S1. Apparent temperature did not co-vary with PM_{10} in any city, but exhibited a 0.66 correlation with ozone in Santiago. The 75th and 95th percentiles of mean apparent temperature are 17.6 and 20.9°C for Santiago, 25.0 and 28.0°C for São Paulo and 16.3 and 18.3°C for Mexico City.

To choose the appropriate ozone and PM_{10} lags, we first included pollution variables in the model individually at single day lags of 0–2 days (Supplementary Figures S1 and S2). Same-day ozone exposure showed the strongest association for all cities. For PM_{10}, lag 1 was strongest for Santiago and lag 0 for São Paulo and Mexico City. We chose those lags for pollution adjustment in subsequent analysis; in all cases, the chosen lags exhibited the highest effect estimates and smallest variance.

We then compared the association between weather and mortality with and without pollution adjustment. Table 2 shows the increased risk in all-cause mortality at the 95th percentile of same-day mean apparent temperature compared with the 75th percentile for each city, with varying degrees of pollutant adjustment. For all cities, effect estimates for weather and mortality were reduced when pollution was included

Table 2 Percentage increase in risk of mortality on days at 95th percentile of same-day mean apparent temperature compared with days at 75th percentile (95% CI), for various pollution adjustment case-crossover models, three Latin American cities, 1998–2002

	Santiago	São Paulo	Mexico City
No pollution adjustment	2.48 (−1.29 to 6.40)	5.19 (3.25 to 7.16)	3.51 (1.90 to 5.14)
Adjusted by PM_{10}	2.43 (−1.35 to 6.36)	4.63 (2.62 to 6.68)	1.35 (−0.29 to 3.02)
Adjusted by ozone	1.82 (−2.08 to 5.87)	4.35 (2.29 to 6.44)	2.53 (0.90 to 4.19)
Adjusted by ozone and PM_{10}	1.82 (−2.08 to 5.88)	4.43 (2.36 to 6.54)	1.26 (−0.39 to 2.93)

All pollution adjustments are at lag 0 except for lag 1 for PM_{10} for Santiago. The 75–95th percentile of mean apparent temperature are 17.6 and 20.9°C for Santiago, 25.0 and 28.0°C for São Paulo and 16.3 and 18.3°C for Mexico City.

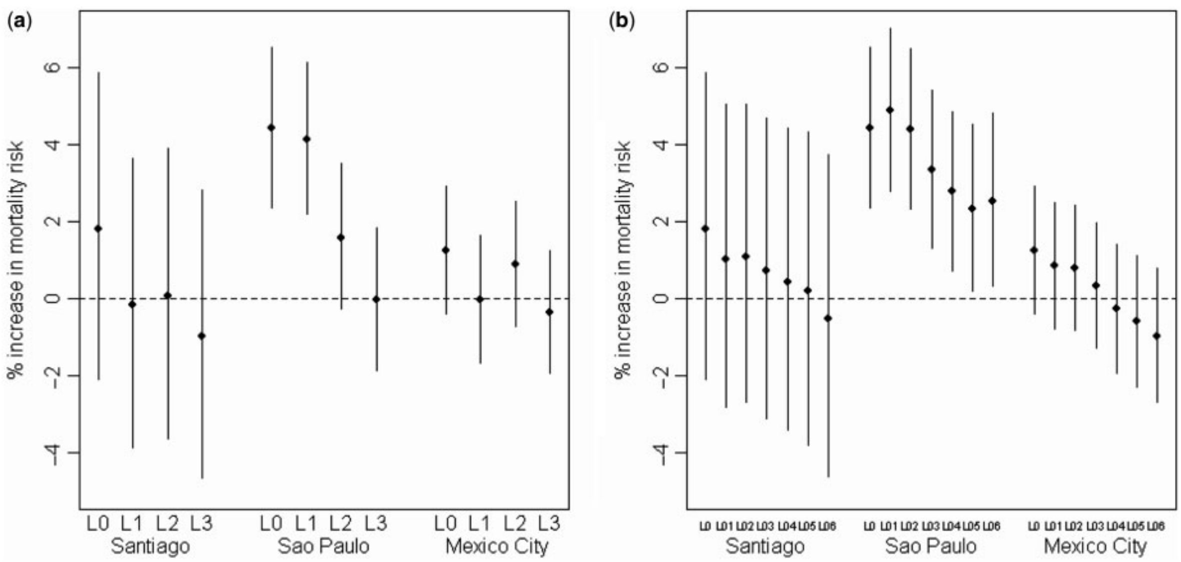

Figure 1 Percent increase in risk of mortality comparing the 95th percentile apparent temperature to the 75th percentile for: (**a**) single day lags of L0–L3 and (**b**) cumulative lags of L0–L06. (The points reflect the central estimate and the vertical lines the 95% CI.)

in the model, for either PM_{10} or ozone, either individually or simultaneously. Reductions were more dramatic for ozone in Santiago, for which ozone and mean apparent temperature were more correlated than in other cities. The reduction in effect estimates were larger with PM_{10} than ozone adjustment in Mexico City. All subsequent models adjust for ozone and PM_{10}.

For apparent temperature, we considered single day lags of 0–3 days and cumulative lags up to the previous week. Figure 1 provides city-specific results with various lag structures for apparent temperature. For single day lags (Figure 1a) of the same day up to 3 days previous, the strongest association was for the same day for all communities. For cumulative exposure lags (Figure 1b), strongest associations were for recent days of exposure and generally declined as longer lag times were incorporated. All subsequent analysis is based on same day apparent temperature.

Changes in mortality risk based on a specific temperature increment (e.g. 10°C) or a comparison of specific percentiles (e.g. 95–75th percentile) provide insight into only a portion of the temperature-mortality curve. To provide a more complete insight, we generated city-specific non-linear relationships between apparent temperature and mortality risk (Figure 2). While risk increases with rising temperatures in all cases, each community's curve has a different shape. The increase in mortality risk per unit temperature increase is higher for São Paulo as shown by the steeper slope on the right-hand side of the curve. The larger uncertainty for Santiago's curve may relate to its smaller sample size. Note that the minimum mortality temperature, above which higher apparent temperatures are associated with increased mortality risk, also differs by city: 11.0°C for Santiago, 20.5°C for Sao Paulo and 12.3°C for Mexico City.

Table 3 compares mortality risk at the 95th and 75th percentiles of apparent temperature, by cause of death, sex, age and educational attainment. No consistent trend was observed for the association between temperature and cause of death across cities. Results by cause of death were strongest for respiratory-related mortality in São Paulo.

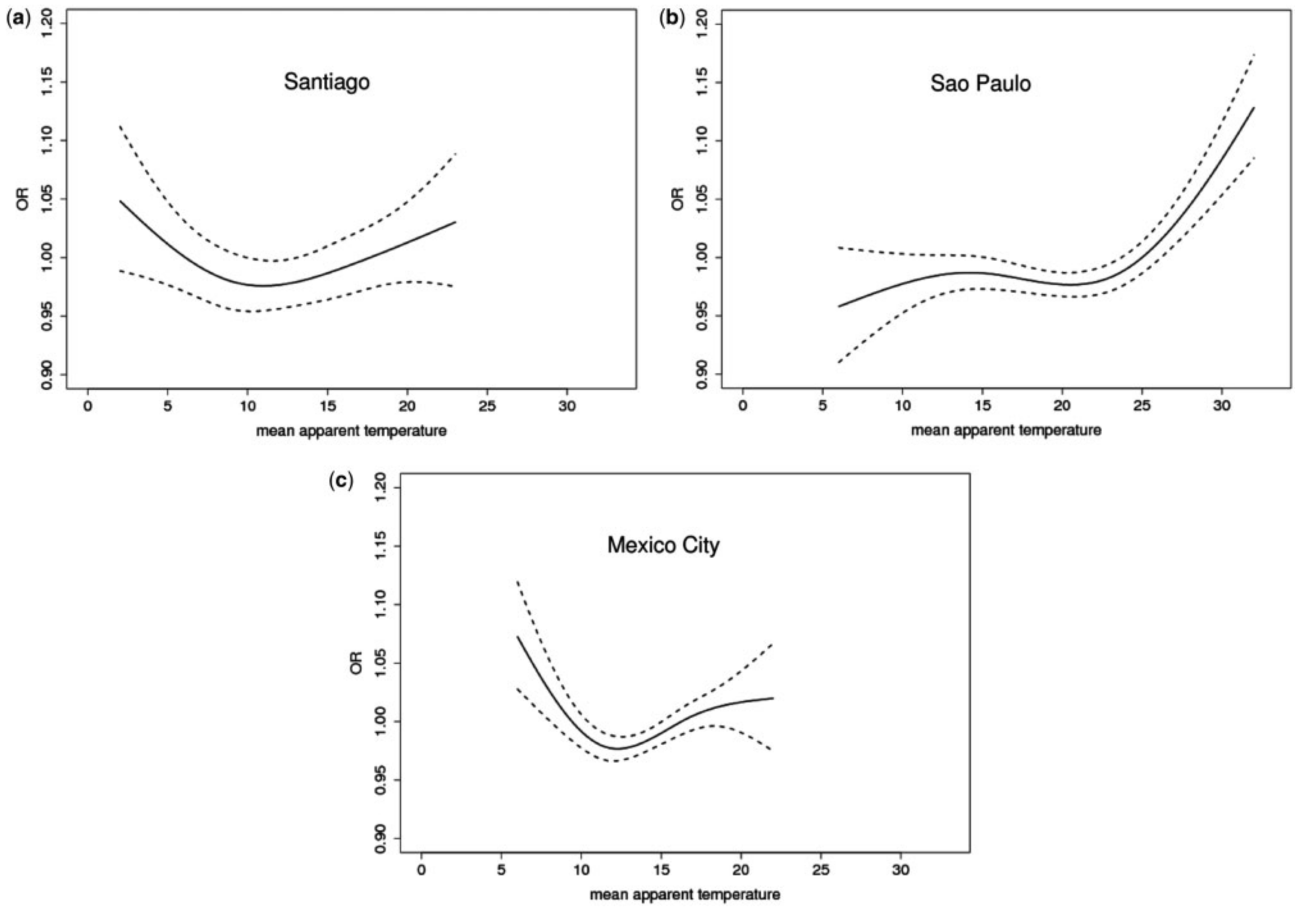

Figure 2 Exposure–response curves for mean apparent temperature and risk of mortality for: (**a**) Santiago; (**b**) São Paulo and (**c**) Mexico City. *Note:* The solid lines reflect the central estimate and the dashed lines the 95% CI. All models are adjusted for ozone at lag 0 for all cities and for PM_{10} at lag 1 for Santiago and lag 0 for Mexico City and São Paulo

Similarly, susceptibility by sex differed by community. While effect estimates for men and women were comparable for any city, associations were higher for men in Santiago and São Paulo and for women in Mexico City. The association between temperature and mortality by education level differed by community. The highest effect estimates were observed for the most educated in Mexico City and the least educated in São Paulo. Older persons were consistently more susceptible. Trends in increasing risk with age were observed in all communities (Supplementary Figure S3), and effects were strongest in the oldest age category ($\geqslant$65) in São Paulo and Mexico City.

We also considered multiple susceptibilities, although the sample size for such analysis is more limited than for our general analysis. Of the factors examined in Table 3 (cause of death, sex, educational attainment and age), the strongest impact on heat-related mortality consistent across cities was for age, with higher effects in the older age categories. Therefore, we further examined this age group with multiple susceptibilities, examining whether mortality risk varied by cause of death, sex or educational level for those $\geqslant$65 years (Supplementary Table S2). For this older population, the strongest effect was for respiratory death in São Paulo. Effects for men and women were not dramatically different for any city within the oldest age category. However, central estimates of association showed higher effects for women in São Paulo and men in Mexico City. For education level, a strong effect for those with a primary education remained in São Paulo when the dataset was restricted to observations $\geqslant$65 years. However, a positive association also was observed for those with the highest education level (university).

São Paulo results show a gradient of associations by educational attainment with higher estimates for lower education (Table 3). Thus, we further examined the association between heat and mortality risk by education within this city by other potential susceptibilities. Supplementary Table S3 provides results by education further stratified by sex in São Paulo. The strongest association remains for those with a primary education, with indication of an association for women with a university degree, but with less evidence for men with this educational training.

Table 3 Percentage increase in risk of mortality at the 95th percentile of mean apparent temperature compared with the 75th percentile (95% CI) by cause of death, sex, age and educational attainment

	Santiago	São Paulo	Mexico City
All observations	1.82 (−2.08 to 5.88)	4.43 (2.36 to 6.54)	1.26 (−0.39 to 2.93)
Cause of death			
Cardiovascular	3.15 (−4.46 to 11.35)	3.30 (−0.14 to 6.86)	2.06 (−1.20 to 5.43)
Respiratory	2.74 (−12.4 to 20.52)	12.22 (3.09 to 22.41)	−7.15 (−15.43 to 1.95)
Sex			
Male	1.98 (−3.42 to 7.68)	4.59 (1.76 to 7.50)	0.78 (−1.54 to 3.15)
Female	1.65 (−3.90 to 7.50)	4.25 (1.25 to 7.34)	1.75 (−0.57 to 4.13)
Education (⩾21 years)			
None	0.58 (−16.00 to 20.34)	7.45 (0.78 to 14.56)	1.30(−2.86 to 5.64)
Primary	2.15 (−3.16 to 7.76)	6.01 (2.70 to 9.43)	1.81 (−1.50 to 5.23)
Secondary	7.11 (−4.25 to 19.83)	4.67 (−2.29 to 12.13)	1.29 (−1.34 to 3.98)
University	1.04 (−6.64 to 9.36)	5.28 (−3.16 to 14.45)	5.50 (−0.82 to 12.21)
Age			
0–15 years	−7.65 (−23.92 to 12.10)	−0.82 (−6.44 to 5.13)	−2.53 (−7.17 to 2.33)
16–64 years	1.10 (−5.80 to 8.53)	3.32 (−0.05 to 6.80)	−0.34 (−3.06 to 2.46)
⩾65 years	2.69 (−2.06 to 7.88)	6.51 (3.57 to 9.52)	3.22 (0.93 to 5.57)

All models are adjusted for ozone at lag 0 for all cities and for PM_{10} at lag 1 for Santiago and lag 0 for Mexico City and São Paulo. The 75th–95th percentile of mean apparent temperature are 17.6 and 20.9°C for Santiago, 25.0 and 28.0°C for São Paulo and 16.3 and 18.3°C for Mexico City.

Discussion

High temperatures were associated with mortality risk in the Latin American cities studied, although the nature of the association differed by city. For São Paulo, the temperature above which mortality risk rose with increasing heat was higher than in other cities. Above this temperature, São Paulo exhibited the highest slope (i.e. largest increase in mortality risk per unit temperature increase). Other studies also observed subregional differences in the impact of extreme temperatures on mortality, indicating that results derived in one community may not be applicable elsewhere. Heterogeneity in the temperature-mortality relationship was noted in studies of 11 US cities,[15] low and middle income countries,[31] 6 South Korean cities[42] and 50 US cities.[40] Though air conditioning prevalence has been cited as a factor explaining differences in heat-mortality associations by subgroup in the US,[40] we do not expect air conditioning to play a large role in these mainly temperate Latin American cities, where air conditioning is less common.

The quality of datasets derived from death certificates could be affected by coding errors, incomplete data or medical uncertainties in cause of death, which may differ by country.[43] Official records were estimated to be under-estimates of deaths by 2, 13.7 and 18.7% for Chile, Mexico and Brazil, respectively.[43] Several studies have investigated the validation of death certificate variables,[44–47] yet only a small number of studies researched this issue for Latin America. Work in Brazil examined the validity of death certificate variables for younger populations and external causes of death.[48–53] In general, these studies found good agreement between the variables measured by the investigators and those recorded on death certificates, but identified some discrepancies and recommended improved accuracy in data entry and processing. The quality of data on death certificates and potential differences in quality by city warrants further investigation.

Time-series analysis of Mexico City for 1996–98 found heat effects on mortality to be robust to air pollution adjustment.[29] Similarly, we found that the point estimates of association between heat and mortality were slightly lowered by pollution adjustment, although the decline in estimates was larger with ozone adjustment for Santiago and PM_{10} adjustment for Mexico City. The impact of pollution adjustment will vary by area, depending in part on the relation between temperature and pollution in any given city. For example, daily apparent temperature and ozone were correlated in Santiago, but not in the other cities. Our group analysed the main effect of PM_{10} on mortality risk for these same cities,[54] and positive associations in all cities confirm the need to carefully consider the role of pollution when estimating temperature associations.

Previous studies found that socio-economic factors affect vulnerability to temperature-related mortality. Lower income areas had slightly higher heat-related mortality for adults in four Italian cities.[7] Persons with lower socio-economic status were six times more likely to have heat stroke than those with higher socio-economic status during a 1980 Missouri heat wave.[6] Higher effects for persons with lower socio-economic status were also identified in the US.[5] A time-series study of São Paulo from 1991 to 1994 found little evidence for effect modification of weather-related mortality by socio-economic position estimated at the community-level.[27] A case-only analysis of those >65 in Sao Paulo in the same time period found higher impacts at the lowest quartile of community-level socio-economic position compared with the highest quartile.[26] In our study, patterns of vulnerability by education differed by city, indicating variation in the role of socio-economic factors in susceptibility, even within the same region of the world. This variation among cities corresponds with earlier work indicating that the relationship between socio-economic factors and health varies by and within country, although this issue is less-studied for Latin American than for more developed regions.[55]

Health may be affected by socio-economic position through baseline health status, nutrition, access to health care, housing characteristics and behaviour patterns, as well as other health risks that may co-vary with socio-economic factors (e.g. smoking). The nature of susceptibility by socio-economic position is far more complex than can be captured by our use of a single marker, educational attainment.[56] Education alone is one of many factors relating to overall socio-economic position, and may not capture changes in an individual's position over time. For example, education has been linked to the onset of chronic health conditions, whereas other indicators such as income were more predictive of progression of chronic conditions.[57] The association between socio-economic indicators and health response can differ by study,[58] and this association can interact with other factors affecting susceptibility, such as age.[59]

Earlier work investigated vulnerability by age and sex. One previous study found higher associations between temperature and mortality for women and older persons.[7] The impact of heat on mortality was larger for women than men in four Italian cities during the 2003 heat wave, and older age groups ($\geqslant$75 years) were more affected than younger groups.[8] The rate of heatstroke was 12 times higher for individuals $\geqslant$65 years than for younger persons during a 1980 heat wave in St Louis and Kansas City, Missouri.[6] We found no dramatic differences between impacts for men and women, although the older age category was consistently at higher risk.

Only a limited number of studies have examined heat-related mortality for Latin America, and only a few of these examined factors affecting vulnerability.[26–30] Most of these studies used time-series approaches within a single city. Our study is the first to our knowledge to apply a case-crossover design to evaluating temperature and mortality in this region. While the inference from time-series and case-crossover methods is comparable,[14] the case-crossover approach allows more refined control for individual-level characteristics. Our study is also, to our knowledge, the first multi-city study to examine vulnerability to temperature-related mortality in Latin America. Our analysis of multiple cities with a common analytic framework and study design has the strength of allowing comparison across communities.

Findings indicate higher risk of heat-related mortality for older populations, although vulnerability by sex and education differed by city. Understanding the nature of vulnerable populations with respect to extreme temperatures is of critical importance given potential changes in climate with higher overall temperatures and frequency of heat waves.[60–62] Research on heat-related mortality with climate change requires not only exposure–response functions of temperature and mortality, but information on how these associations differ by city, how susceptibility differs by population within the community and how such factors (e.g. age distribution) may change over time.[63] For example, susceptibility to heat-related mortality declined in the 20th century in London, possibly from changes in factors affecting susceptibility such as housing characteristics and population demographics.[19] Future studies of the relationship between temperature and health, including variation in vulnerability, in different regions can help guide efforts to address heat-related mortality and research on the human health consequences of climate change.

Supplementary Material

Supplementary data are available at *IJE* online.

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KEY MESSAGE

- In three large Latin American cities with temperate climates, a higher risk of heat-related mortality was observed among older individuals, although associations in Santiago, Chile were imprecise. Vulnerability to heat-related mortality by sex and education differed by city. These results suggest that adaptation efforts in these cities to respond to the increasing intensity, frequency and duration of heat waves expected under climate change should target older populations, and that other prevention efforts will require tailoring to the unique population vulnerabilities within each community.

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