International Journal of Hygiene and Environmental Health 248 (2023) 114109

Contents lists available at ScienceDirect

International Journal of Hygiene and Environmental Health

journal homepage: www.elsevier.com/locate/ijheh

Heat waves and mortality in the Brazilian Amazon: Effect modification by heat wave characteristics, population subgroup, and cause of death

Ismael Henrique Silveira [a,*], Shaiana Vilella Hartwig [b], Maurício Nascimento Moura [a,c], Taísa Rodrigues Cortes [d], Washington Leite Junger [d], Glauber Cirino [c], Eliane Ignotti [e], Beatriz Fátima Alves de Oliveira [f]

[a] Institute of Collective Health, Federal University of Bahia, Salvador, Brazil
[b] School of Health Sciences, Mato Grosso State University, Cáceres, Brazil
[c] Geosciences Institute, Federal University of Pará, Belém, Brazil
[d] Institute of Social Medicine, Rio de Janeiro State University, Rio de Janeiro, Brazil
[e] Postgraduate Program in Environmental Sciences, Mato Grosso State University, Cáceres, Brazil
[f] Fiocruz Regional Office in Piauí, National School of Public Health, Oswaldo Cruz Foundation, Teresina, Brazil

ARTICLE INFO

Handling Editor: Dr. A Calafat

Keywords:
Heat waves
Climate change
Mortality
Vulnerability
Amazon

ABSTRACT

Background: The Brazilian Amazon faces overlapping socio-environmental, sanitary, and climate challenges, and is a hotspot of concern due to projected increases in temperature and in the frequency of heat waves. Understanding the effects of extreme events on health is a central issue for developing climate policies focused on the population's health.
Objectives: We investigated the effects of heat waves on mortality in the Brazilian Amazon, examining effect modification according to various heat wave definitions, population subgroups, and causes of death.
Methods: We included all 32 Amazonian municipalities with more than 100,000 inhabitants. The study period was from 2000 to 2018. We obtained mortality data from the Information Technology Department of the Brazilian Public Healthcare System, and meteorological data were derived from the ERA5-Land reanalysis dataset. Heat waves were defined according to their intensity (90th; 92.5th; 95th; 97.5th and 99th temperature percentiles) and duration (≥2, ≥3, and ≥4 days). In each city, we used a time-stratified case-crossover study to estimate the effects of each heat wave definition on mortality, according to population subgroup and cause of death. The lagged effects of heat waves were estimated using conditional Poisson regression combined with distributed lag non-linear models. Models were adjusted for specific humidity and public holidays. Risk ratios were pooled for the Brazilian Amazon using a univariate random-effects meta-analysis.
Results: The pooled relative risks (RR) for mortality from total non-external causes varied between 1.03 (95% CI: 1.01–1.06), for the less stringent heat wave definition, and 1.18 (95% CI: 1.04–1.33) for the more stringent definition. The mortality risk rose as the heat wave intensity increased, although the increase from 2 to 3, and 3–4 days was small. Although not statistically different, our results suggest a higher mortality risk for the elderly, this was also higher for women than men, and for cardiovascular causes than for non-external or respiratory ones.
Conclusions: Heat waves were associated with a higher risk of mortality from non-external causes and cardiovascular diseases. Heat wave intensity played a more important role than duration in determining this risk. Suggestive evidence indicated that the elderly and women were more vulnerable to the effects of heat waves on mortality.

1. Introduction

Heat waves are meteorological events characterized by high temperatures that last for several days, are among the most dangerous of natural hazards and can have significant health impacts (WMO and WHO, 2015). They are associated with increased morbidity, including

* Corresponding author. Instituto de Saúde Coletiva, Universidade Federal da Bahia, Rua Basílio da Gama s/no, Canela, Salvador, BA, Cep: 40110-040, Brazil.
E-mail address: ismaelhsilveira@gmail.com (I.H. Silveira).

https://doi.org/10.1016/j.ijheh.2022.114109
Received 19 August 2022; Received in revised form 23 December 2022; Accepted 30 December 2022
Available online 2 January 2023
1438-4639/

hospitalizations, ambulance call-outs and emergency department visits, and with general mortality from non-external and specific causes (Campbell et al., 2018; Li et al., 2015; Son et al., 2019; Xu et al., 2016; Zuo et al., 2015), principally cardiorespiratory outcomes (Cheng et al., 2019).

The effects of heat waves on the population's health are not homogeneous, and may vary by location and study population. The groups most vulnerable to the effects of heat waves include the elderly, people of low socioeconomic status, heavy-duty workers, individuals with a pre-existing condition, and residents from deprived areas with poor housing conditions, including a lack of air conditioning or ventilation mechanisms (Li et al., 2015; Son et al., 2019; Song et al., 2017). Exposure of the vulnerable (such as children and the elderly) to heat waves has increased in recent years, and there is an increasing trend in heat-related mortality for populations over 65 years (Romanello et al., 2021; Watts et al., 2021).

According to the Intergovernmental Panel on Climate Change (IPCC, 2022), the global surface temperature has increased over recent decades, and extreme events, such as heat waves, are becoming more frequent and intense. Projections based on climate change scenarios indicate that temperatures will continue to rise, and heat waves will become even more severe (IPCC, 2022). Accordingly, an increase in heat- and heat wave-related mortality is expected (Deng et al., 2018; Guo et al., 2018; Sanderson et al., 2017).

The climate in the Amazon region is predominantly hot and humid, with average temperatures over 25 °C, although some locations experience periods of drought. The air temperature over the region has been increasing (Marengo et al., 2018), and projections based on climate models consistently show increases in temperature variability and in the frequency of heat waves in the region (Bathiany et al., 2018; Feron et al., 2019). Another cause for concern is the recent and growing trend in forest fires and deforestation (Hope, 2019; Qin et al., 2021). In addition, the region still faces old socio-environmental and sanitary challenges, which may be exacerbated by the climate crisis, especially in a context of population growth predominantly concentrated in urban centers (Garnelo, 2019; Viana et al., 2016).

The Brazilian Amazon consists of 772 municipalities and 9 states, covers 58.9% of Brazil's territory, and has an estimated population of 28,113,186 inhabitants - 13.3% of the country's population (IBGE, n.d.). It has complex socio-environmental characteristics, with urban centers coexisting with relatively small and isolated towns and villages, and traditional populations (indigenous, quilombolas and riverine peoples) of different ethnicities dispersed across remote rural areas (Garnelo, 2019). The highly predatory development model implemented in the Amazon has led to significant environmental changes, without improving its social or health characteristics. The region has the worst socio-environmental indicators in the country, with high levels of extreme poverty, the lowest human development index, and sanitation coverage well below the national average. Its health indicators, including infant mortality and incidence of infectious diseases, such as dengue, leishmaniasis and leprosy, are also worse than the national average (Viana et al., 2016).

Action and climate policies focusing on the population's health and well-being are urgently required (Yglesias-González et al., 2022). Understanding the effects of climate and climate change on health, highlighting the most vulnerable populations, is a central feature of such action, especially in a region that experiences overlapping socio-environmental, health, and climate challenges. There is a lack of scientific evidence about the effects of heat waves in the Amazon, or in other tropical regions in low- and middle-income countries (Campbell et al., 2018; Son et al., 2019; Xu et al., 2016). Most of the studies on the mortality effects of heat waves in Brazil were restricted to São Paulo (Diniz et al., 2020; Moraes et al., 2022; Son et al., 2016), or focused on heat wave effects at the national level (Guo et al., 2017). In this study, we investigate the effects of heat waves on mortality in the Brazilian Amazon region. Furthermore, we examined how these vary according to different definitions of heat waves, and across different population subgroups and causes of death.

2. Methods

2.1. Study location

We included municipalities with more than 100,000 inhabitants, according to the 2010 Census, giving a total of 32 municipalities: Rio Branco in Acre State; Manaus and Parintins in Amazonas; Macapá and Santana in Amapá; Belém, Altamira, Ananindeua, Santarém, Marabá, Castanhal, Parauapebas, Abaetetuba, Cametá, Bragança and Marituba in Pará; Porto Velho and Ji-Paraná in Rondônia; Boa Vista in Roraima; Palmas and Araguaína in Tocantis; São Luís, Imperatriz, São José de Ribamar, Codó, Paço do Lumiar, Açailândia and Bacabal in Maranhã; Cuiabá, Várzea Grande, Rondonópolis and Sinop in Mato Grosso (Fig. 1). Municipal socio-demographic and geographic information is presented in Supplementary Table S1.

2.2. Data

2.2.1. Mortality and individual-level data

We calculated daily deaths based on mortality data from non-external causes (codes A00 to R99 of the 10th International Classification of Diseases), obtained from the Mortality Information System (SIM) of the Information Technology Department of the Public Healthcare System (DATASUS). The study covered the period from 2000 to 2019, and included information on age, gender and cause of death.

2.2.2. Meteorological data

We calculated the daily weather variables – mean temperature, maximum temperature and specific humidity – based on the ERA5-Land reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ECMWF) for the study period. The ERA5-Land provides hourly data with a grid resolution of 9 km. Daily variables were calculated from hourly data. Gridded data was attributed to each municipality by calculating the weighted average of the grids covered by a 20 km circular buffer centered on the municipality's main offices. We compared the temperature from the ERA5-Land and ground-level

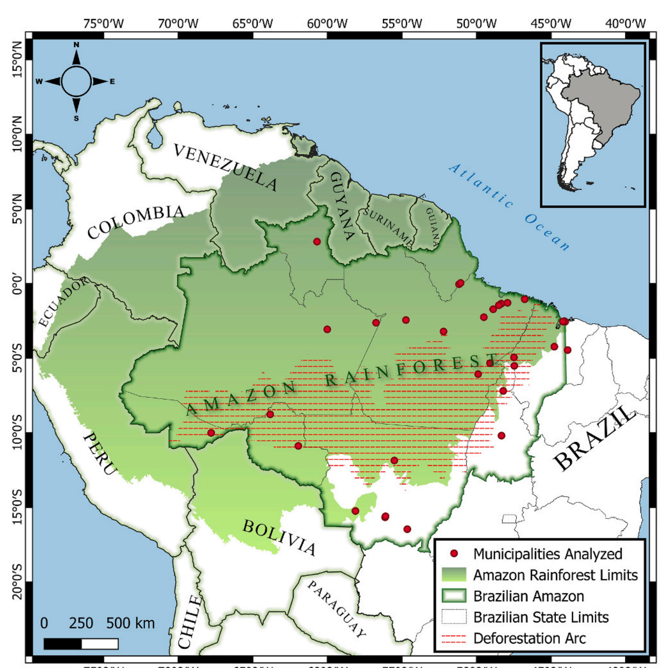

Fig. 1. Study area.

weather stations, examining the Pearson correlation for these series in 17 cities where data were available. Additional details about these data are presented in Supplementary Table S2.2.3 Heat wave definitions.

While there is no unique definition for heat waves, it is understood that they refer to prolonged periods of unusually hot temperatures (WMO, 2015). Generally, definitions differ in relation to their temperature metric, duration (days, weeks), and intensity (temperature threshold), which can be absolute or relative, based on temperature distribution percentiles over a certain period (Xu et al., 2016; Zuo et al., 2015). The best criteria may vary between different regions, and what is considered a climatic extreme in one place may not be considered so in another (Zuo et al., 2015). In order to better understand the effect of heat waves on mortality, we used fifteen definitions, which varied according to heat wave intensity (90th; 92.5th; 95th; 97.5th and 99th percentiles of the daily mean temperature over the study period) and duration (≥2, ≥3, and ≥4 days). We used the mean temperature as it is more likely to represent the heat level in 24 h (Xu et al., 2016). We did not restrict our analysis to the hottest season as temperatures in the region are generally high throughout the year.

2.3. Study design and analysis

In the first stage of analysis, we used a case-crossover study for each city to estimate the effects of each heat wave definition on mortality, and across different population subgroups (people aged 0–64, people aged 65 or above, men and women) and causes of death (cardiovascular and respiratory diseases). In case-crossover studies, the individuals who experienced the event of interest serve as their own controls, and exposure on the day of the event (case period) is compared with exposure at different times (control periods) (Maclure, 1991). We used the time-stratified control selection strategy, whereby controls are selected on the same day of the week, month, and year as the cases (Janes et al., 2005).

We used a directed acyclic graphic (DAG) to explain the causal hypotheses underlying our study and to identify a sufficient set of adjustment variables to estimate the total effect of heat waves on mortality outcomes (Supplementary Fig. S1). The DAG was created in DAGitty (Textor et al., 2011). Because participants are compared with themselves at different points in time, time-invariant confounders, such as individual characteristics, are adjusted by design (Maclure, 1991). Furthermore, since the cases were matched to controls on the same day of the week, month and year, the potential confounding effects of day of the week, long-term trend, and seasonality were also avoided (Janes et al., 2005). The sufficient set of variables for adjustment to estimate the total effect of heat waves on mortality in our regression model therefore included specific humidity and public holidays. Since relative humidity is a function of temperature, we adjusted for specific humidity rather than relative humidity, potentially reducing over-fitting (Davis et al., 2016). Air pollution was considered a potential mediator and thus was not included in the models.

We ran conditional Poisson regression models (Armstrong et al., 2014) to estimate the effect of heat waves on mortality. Heat waves were represented by a binary variable (0 for non-heat wave days, 1 for heat wave days) while distributed lag non-linear models (DLNM) (Gasparrini et al., 2010) were used to account for their delayed effects. We used a linear function to represent the effect of exposure, and a natural cubic spline, with four degrees of freedom, over the 5-day lag period. The choice of model parameters, spline function and number of knots, was based on a minimization of the sum of the Akaike Information Criteria for quasi-Poisson models. According to our analyses, 5 days is sufficient to account for the delayed effect and any potential harvesting effect (Supplementary Fig. S2). Specific humidity was controlled using a natural cubic spline with 3 degrees of freedom, while public holidays were controlled using a binary variable. The formula representing the conditional Poisson regression model used to estimate the city-specific heat wave-mortality association is in the supplementary material.

In the second stage, we used univariate random-effects meta-analyses (Gasparrini and Armstrong, 2013) to pool the city-specific results and obtain a summary measure for the entire Brazilian Amazon. The regression coefficients of the first stage models were reduced, cumulating the lag-specific contribution, and then used as outcomes for the meta-analyses with the intercept only. The pooled mortality risks were estimated for all definitions of heat waves and each subgroup.

Since the locations studied have different climatic and socioeconomic characteristics, we tested the heterogeneity between the city-specific heat wave-mortality association using the multivariate Cochran Q test and I^2 statistic. We fitted a meta-regression model to assess whether the exposure-outcome association changes according to certain meteorological, socioeconomic and geographical characteristics at city level. We tested the meta-predictors: average mean, minimum and maximum temperatures, mean annual temperature range, the Köppen climate classification, and latitude. The associations between the meta predictors and the exposure-response reduced coefficients were tested using the Wald test. We used the meta-analytical model with average maximum temperature at city level to derive the best linear unbiased prediction (BLUP) (Gasparrini et al., 2012) of heat wave-mortality in each city. Associations predicted with BLUP correspond to a trade-off between the city-specific and pooled associations, allowing locations with a low number of daily deaths to borrow information from locations which have similar characteristics but a higher number of deaths (Gasparrini et al., 2012, 2015).

2.3.1. Sensitivity analyses

We performed certain sensitivity analyses to verify the robustness of our results. For the lagged effects, we used a quadratic b-spline, natural cubic splines with 3 and 5 degrees of freedom and different lag periods (10 and 21 days). Different adjustments were explored, including a model without humidity and a model adjusted for temperature to investigate whether there was an additional effect of heat waves on mortality above the effect of high temperature on the first heat wave day, in line with Guo et al. (2017). We used a natural cubic spline with 4 degrees of freedom, with equally spaced knots, for both temperature and 5-day lag. Finally, the maximum temperature was used to define heat waves. Sensitivity analyses were pooled for the entire Brazilian Amazon, and the results were reported for heat wave definitions with a duration of at least 2 days.

All procedures and statistical analyses were conducted in R software (version 4.1.1), with the microdatasus package to download health data, ecmwfr to download weather data, gnm and dlnm for the city-specific analyses and mvmeta for the meta-analyses.

3. Results

Between 2000 and 2019, there were 831,084 deaths from all non-external causes, 199,330 (24%) from cardiovascular diseases and 85,598 (10.3%) from respiratory ones. The majority occurred among men (58.2%) and people aged up to 64 (52.2%). Supplementary Table S3 presents the descriptive statistics of the outcomes and meteorological variables for each of the 32 cities included in the study, while Table 1 presents a summary of the averages for these cities.

Table 2 shows the average, minimum and maximum number of heat wave days in the cities studied, according to each definition criteria. The number of heat wave days in the 32 municipalities in this study, according to the fifteen heat wave definitions applied, are presented in Supplementary Table S4. As the heat wave definition became more stringent, with increasing duration and intensity, the average, minimum, and maximum numbers of heat wave days fell.

The results of the I^2 statistic and the p-value of the Cochran Q test for the meta-regression with intercept only, equaling 25.9% and 0.093 respectively, suggest that the residual heterogeneity of the association between cities is not high, and not significant at the 5% confidence level (Supplementary Table S5). However, the residual heterogeneity was

Table 1
Summary statistics of the daily mean deaths and meteorological variables in the 32 cities in the Brazilian Amazon.

	Total (and %)	Mean	SD	Min	Median	Max
Total non-external mortality	831,084	3.5	5.3	0.3	1.6	22.2
Male	483,863 (58.2%)	2.1	3	0.2	0.9	12.9
Female	346,561 (41.7%)	1.5	2.3	0.1	0.6	9.3
0–64 years old	433,833 (52.2%)	1.9	2.8	0.1	0.8	12.5
65 years old or above	397,121 (47.8%)	1.7	2.5	0.2	0.8	10.7
Cardiovascular mortality	199,330 (24.0%)	0.9	1.2	0.1	0.4	5.1
Respiratory mortality	85,598 (10.3%)	0.4	0.6	0	0.2	2.8
Average temperature (°C)	–	26.4	0.5	25.4	26.5	27.4
Average specific humidity (kg/kg)	–	0.014	0.001	0.013	0.014	0.015

Table 2
Average, minimum, and maximum number of heat wave days for fifteen heat wave definitions, across 32 cities in the Brazilian Amazon (2000–2019).

Abbreviation	Definition (days, percentile threshold)	mean	minimum	maximum
hw2_90	2 days, 90th	599.5	511.0	671.0
hw2_925	2 days, 92.5th	429.7	363.0	523.0
hw2_95	2 days, 95th	277.8	216.0	330.0
hw2_975	2 days, 97.5th	124.5	90.0	156.0
hw2_99	2 days, 99th	49.25	35.0	62.0
hw3_90	3 days, 90th	468.8	367.0	553.0
hw3_925	3 days, 92.5th	321.7	268.0	420.0
hw3_95	3 days, 95th	198.6	137.0	248.0
hw3_975	3 days, 97.5th	83.28	53.0	119.0
hw3_99	3 days, 99th	29.53	18.0	48.0
hw4_90	4 days, 90th	379.6	270.0	475.0
hw4_925	4 days, 92.5th	250.8	181.0	358.0
hw4_95	4 days, 95th	148.4	93.0	201.0
hw4_975	4 days, 97.5th	57.22	30.0	92.0
hw4_99	4 days, 99th	18.12	7.0	40.0

even lower in the models that contained (separately) the variables: temperature range, and maximum and minimum temperature, which, according to the Wald test, modified the heat wave-mortality association. When we tested the multivariate meta-regression model with these three meta variables, only the maximum temperature remained significantly associated at the 5% level. Given this, and observing the goodness of fit criteria (AIC and BIC), we chose to use the model with the maximum temperature only to derive the BLUP for the city-specific heat wave-mortality association. For this paper we have chosen to present the combined results for the entire region, while the city-specific results are reported in the supplementary material.

Fig. 2 shows the pooled relative risks (RR) and their 95% confidence intervals for the effect of heat waves on mortality, according to the different definitions analyzed, over a lag period of 0–5 days. Although not statistically different, we found higher mortality risk as the heat wave intensity increases (higher thresholds), while there is a small increase as the duration changes from 2 to 3 days (for 95th percentile thresholds or higher), but no difference for a duration of 4 days. The pooled RR for mortality from total non-external causes, comparing heat wave days to non-heat wave days, varied between 1.03 (95% CI: 1.01–1.06), for the less stringent heat wave definition, and 1.18 (1.04–1.33) for the more stringent definition. Most city-specific results (Fig. S3) had a pattern similar to the pooled association, with risks increasing with heat wave intensity, albeit with a higher occurrence of

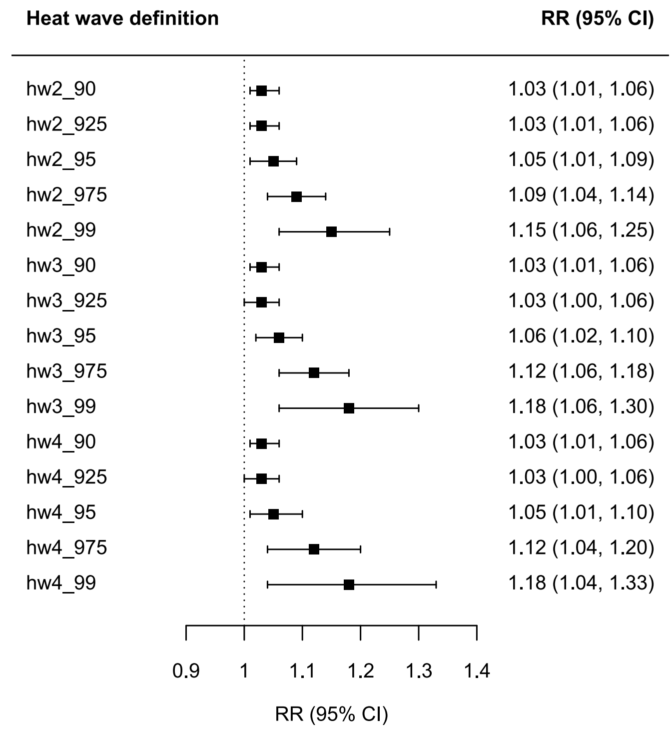

Fig. 2. Pooled effect of heat waves on mortality in the Brazilian Amazon over a lag period of 0–5 days, with heat waves of varying duration and intensity.

non-significant results at the 5% level.

Table 3 presents the relative risks of mortality due to heat waves by subgroup. We have reported the results for heat waves lasting at least 2 days, because this is a less rigorous criterion with a greater number of heat wave days, for the lowest (90th percentile), intermediate (95th), and highest heat wave intensity (99th). Results stratified by age, sex and cause of death were not statistically different, but suggest that the effect was greater for the elderly (≥65 years), and close to the null value for the younger subgroup (0–64 years). Both men and women experienced an increased risk of mortality on heat wave days, but the central RR estimates were greater for women. Although not statistically different, the results also suggest a greater effect for cardiovascular mortality than for non-external and respiratory causes. Supplementary Table S6 shows the stratified results for all the heat wave definitions.

Sensitivity analyses (Supplementary Table S7) show that these results remain robust when the model specifications change. The pooled results for the Brazilian Amazon were similar for a quadratic b-spline function and a natural cubic spline with 3 and 5 degrees of freedom for the lag-response relationship, and when specific humidity was removed from the model. For the longer lag period, we observed a reduction in

Table 3
Overall effect of heat waves on mortality in the Brazilian Amazon, over a lag period of 0–5 days, stratified by age, gender and cause of death. Heat waves of two or more days and varying intensity.

Subgroup	Risk ratio (95% confidence interval)		
	Lowest intensity (90th)	Intermediate intensity (95th)	Highest intensity (99th)
All causes	1.03 (1.01–1.06)	1.05 (1.01–1.09)	1.15 (1.06–1.25)
0–64 years old	1.00 (0.97–1.03)	0.99 (0.96–1.03)	1.03 (0.95–1.12)
65 years or above	1.07 (1.03–1.12)	1.12 (1.05–1.19)	1.34 (1.15–1.57)
Male	1.02 (0.99–1.05)	1.05 (1.01–1.08)	1.11 (1.01–1.22)
Female	1.04 (0.99–1.09)	1.07 (1.00–1.14)	1.24 (1.07–1.43)
Cardiovascular	1.06 (1.02–1.1)	1.07 (1.01–1.13)	1.27 (1.13–1.42)
Respiratory	1.09 (0.98–1.22)	1.07 (0.96–1.21)	1.05 (0.73–1.52)

the relative risks, but the reductions were smaller during the more intense heat waves. When we used the maximum temperature to define heat waves, the effects were slightly greater. When we controlled for temperature, the effect became null, except during the highest intensity heat wave, suggesting that there is an added effect from high intensity heat waves beyond the temperature effect.

4. Discussion

We carried out a time-stratified case-crossover study and a univariate random-effects meta-analysis to estimate the effect of heat waves on mortality in the Brazilian Amazon, according to heat wave definitions, population subgroups and causes of death. Our findings show that heat waves increased the risk of mortality in the Brazilian Amazon, and this risk increased with more intense heat waves. The evidence suggests that the elderly (≥65 years) were more vulnerable to heat wave effects than the younger population, women were more vulnerable than men, and the risk was higher for cardiovascular mortality than for non-external mortality and respiratory causes.

The effect of heat waves on mortality that we observed is consistent with the literature (Campbell et al., 2018; Xu et al., 2016; Zuo et al., 2015), although few studies have analyzed the effect of heat waves on health in Brazilian locations. Findings for Brazil in a multi-country study evidenced both the main effect, due to high temperatures, and the additional effect, due to heat wave duration, on all-cause mortality (Guo et al., 2017). Studies conducted in the city of São Paulo identified an increase in the risk of mortality from all-cause mortality and cardiorespiratory outcomes (Diniz et al., 2020; Moraes et al., 2022; Son et al., 2016).

Most heat-related health outcomes have cardiorespiratory causes (Cheng et al., 2019). The physiological mechanisms underlying these effects are usually explained by cardiovascular changes induced by thermoregulatory responses (Cheng et al., 2019; Kenney et al., 2014; Song et al., 2017). Thermoregulatory responses to high temperature exposure cause an increase in blood flow to the skin and sweating to dissipate heat, Consequently, there is an increase in both respiratory rate and heart rate, causing additional stress, particularly to the heart and lungs, increased dehydration, blood viscosity, and blood pressure (Deng et al., 2018; Hanna and Tait, 2015; Kenney et al., 2014; Liu et al., 2015).

We assessed the effects of fifteen heat wave definitions based on intensity (90th, 92.5th, 95th, 97.5th and 99th daily mean temperature percentiles) and duration (≥2, ≥3, e ≥ 4 days). The effects were greater as the intensity of the heat waves increased, but little change was seen with increased duration. Similar results have been found in other studies (Diniz et al., 2020; Guo et al., 2017; Moraes et al., 2022), and these results corroborate the conclusion of a systematic review which concluded that heat wave intensity plays a more important role than duration in determining the effects on mortality (Xu et al., 2016). The more intense or longer-lasting the heat wave, the greater the load on the cardiovascular system to perform thermoregulation (Chen et al., 2020).

In relation to cause of death, the effects of heat waves on mortality were higher for cardiovascular causes than non-external ones. The effects on respiratory mortality were not consistent. A meta-analysis study reported that heat waves were associated with an increased risk of mortality from cardiovascular and respiratory diseases (Cheng et al., 2019). In addition, the effects of heat waves on mortality from respiratory diseases and chronic obstructive pulmonary disease were significant among the elderly. A study conducted in São Paulo observed a higher risk of death from total cardiovascular and respiratory outcomes among women; for men, the risk of mortality from cerebrovascular disease and ischemic stroke was higher (Moraes et al., 2022). In our study, the inconsistency of the effect on respiratory mortality may be associated with our inclusion of all deaths classified by the ICD-10 chapter J, and the fact that we studied the entire population.

Our stratified analyses evidenced the heterogeneity of heat wave effects according to demographic characteristics. In the age-stratified analyses, heat wave effects were only observed among the elderly (≥65 years), which is similar to other studies (Chen et al., 2020; Green et al., 2019; Van den Wyngaert et al., 2021; Yang et al., 2019; Yin et al., 2018). Even in healthy individuals the aging process is accompanied by the degeneration of the physiological functions involved in thermoregulation and limitations in thermal perception, and may be associated with the presence of chronic diseases (Kenney et al., 2014; Zhou et al., 2014).

Both genders had an increased risk of mortality on heat wave days, although women were more vulnerable than men, in line with findings from other studies (Cheng et al., 2018; Yang et al., 2019). A study carried out on the elderly in São Paulo, found that women had a higher risk of mortality from heart and respiratory diseases (Diniz et al., 2020). In a systematic review, Son et al. (2019) found strong evidence that the risk of heat-related mortality is higher for women than men, although some studies have failed to identify a difference or found a higher risk for men. The greater vulnerability of women may be associated with physiological differences, and occupational and exposure patterns between genders (Son et al., 2019). Furthermore, differences in age structure between genders may explain some of this heterogeneity (Benmarhnia et al., 2015).

To the best of our knowledge, this is one of the largest studies carried out on the effects of heat waves on mortality in Brazil and specifically in the Brazilian Amazon. The study accounted for the lagged effects of heat waves, examining the modification of these effects according to different heat wave definitions, causes of deaths and population subgroups.

This evidence has significant public health implications. In the Brazilian Amazon, heat waves can increase the risk of mortality from all non-external causes and from cardiovascular diseases. In addition, older people and women are more vulnerable to the effects of heat waves on mortality. These results highlight the urgent need to develop and implement heat-health action plans for the region, with a specific focus on the most sensitive sectors of society and including the implementation of warning systems and response strategies to reduce the effects of heat waves on health.

This study has certain limitations. Similar to our previous studies on the effect of temperature on mortality in Brazil, exposure classification errors may have occurred (Silveira et al., 2019, 2020). Due to the lack of high-spatial resolution meteorological data, or geocoded health data, heat wave identification was based on a single temperature series for each city. In addition, we used an environmental measure as a proxy for individual exposure and were unable to consider variations in individual exposure related to daily mobility. However, exposure misclassification tends to be random, which could bias the results towards the null (Guo et al., 2017; Lee et al., 2016). In addition, since we used publicly available mortality data, it was not possible to distinguish between the rural and urban populations, which may have revealed important differences related to exposure and vulnerability to heat waves.

Another possible study limitation refers to the use of climate reanalysis, rather than station-based temperature data. According to Mistry et al. (2022), climate reanalysis represents an alternative to a lack of monitoring station data for use in time series analyses of heat-health effects, although, compared to measured temperature, they observed a lower performance in risk estimates in tropical regions, including the Brazilian Amazon. However, the differences in exposure-response associations based on the two temperature sources can be explained by certain factors, including proximity to the coast or hills, the quality and maintenance of the weather monitoring network, the population density in the cities analyzed, etc. We examined Pearson's correlation between the ERA5-Land and station-based temperature for some of the locations in our study area, and found a mean correlation of 0.78, with two locations below 0.70 (Supplementary Table S2). This low correlation may be explained by the sparse monitoring network in the region and less reliable data, with many missing data in the time series. Ground-level measurements are important inputs for reanalysis datasets.

Future studies should examine the role of the socio-environmental and infrastructural determinants of the effect of heat waves on health and the vulnerability of specific subgroups in the Amazonian population. According to the 2010 Census, the region contains almost half of the Brazilian indigenous population, and a high percentage of the quilombola and riverine populations. These people are not historically assisted by public policies, face a series of socio-environmental conflicts, aggravated in recent years by pressures from the agricultural sector, deforestation and illegal mining in the region, and may be more vulnerable to the impacts of climate change. We also need to better understand the role of socioeconomic situation on these findings. Some of these data are not available on death certificates, and the completion of the race/color field is still very limited, since it depends on identification by the responsible physician, and there remains a high proportion of missing data. In addition, studies are required to investigate the modification effect of humidity, environmental pollution, mainly resulting from forest fires, the use of air conditioning, and coverage of public policies, such as cash transfer programs, primary healthcare, and hospital care policies. We could also investigate the use of different thermal indices, that consider, for example, humidity conditions, to classify heat wave events.

5. Conclusion

Our study showed that heat waves in the Brazilian Amazon were associated with a higher risk of mortality from non-external causes and cardiovascular diseases. The mortality risk was higher as the intensity of heat waves increased, which played a more important role in determining risk than duration. In addition, suggestive evidence indicated that older people and women were more vulnerable to the effects of heat waves on mortality.

Funding

This study was supported by the Institute for Climate and Society (iCS), Brazil (grant number G-21-00854).

Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2022.114109.

References

Armstrong, B.G., Gasparrini, A., Tobias, A., 2014. Conditional Poisson models: a flexible alternative to conditional logistic case cross-over analysis. BMC Med. Res. Methodol. 14, 1–6. https://doi.org/10.1186/1471-2288-14-122.

Bathiany, S., Dakos, V., Scheffer, M., Lenton, T.M., 2018. Climate models predict increasing temperature variability in poor countries. Sci. Adv. 4 https://doi.org/10.1126/sciadv.aar5809.

Benmarhnia, T., Deguen, S., Kaufman, J.S., Smargiassi, A., 2015. Review article: vulnerability to heat-related mortality: a systematic review, meta-analysis, and meta-regression analysis. Epidemiology 26, 781–793. https://doi.org/10.1097/EDE.0000000000000375.

Campbell, S., Remenyi, T.A., White, C.J., Johnston, F.H., 2018. Heatwave and health impact research: a global review. Health Place 53, 210–218. https://doi.org/10.1016/j.healthplace.2018.08.017.

Chen, J., Zhou, M., Yang, J., Yin, P., Wang, B., Ou, C.-Q., Liu, Q., 2020. The modifying effects of heat and cold wave characteristics on cardiovascular mortality in 31 major Chinese cities. Environ. Res. Lett. 15, 105009 https://doi.org/10.1088/1748-9326/abaea0.

Cheng, J., Xu, Z., Bambrick, H., Prescott, V., Wang, N., Zhang, Y., Su, H., Tong, S., Hu, W., 2019. Cardiorespiratory effects of heatwaves: a systematic review and meta-analysis of global epidemiological evidence. Environ. Res. 177, 108610 https://doi.org/10.1016/j.envres.2019.108610.

Cheng, J., Xu, Z., Bambrick, H., Su, H., Tong, S., Hu, W., 2018. Heatwave and elderly mortality: an evaluation of death burden and health costs considering short-term mortality displacement. Environ. Int. 115, 334–342. https://doi.org/10.1016/j.envint.2018.03.041.

Davis, R.E., McGregor, G.R., Enfield, K.B., 2016. Humidity: a review and primer on atmospheric moisture and human health. Environ. Res. 144, 106–116. https://doi.org/10.1016/j.envres.2015.10.014.

Deng, Q., Zhao, J., Liu, W., Li, Y., 2018. Heatstroke at home: prediction by thermoregulation modeling. Build. Environ. 137, 147–156. https://doi.org/10.1016/j.buildenv.2018.04.017.

Diniz, F.R., Gonçalves, F.L.T., Sheridan, S., 2020. Heat wave and elderly mortality: historical analysis and future projection for metropolitan region of São Paulo, Brazil. Atmosphere 11, 933. https://doi.org/10.3390/atmos11090933.

Feron, S., Cordero, R.R., Damiani, A., Llanillo, P.J., Jorquera, J., Sepulveda, E., Asencio, V., Laroze, D., Labbe, F., Carrasco, J., Torres, G., 2019. Observations and projections of heat waves in south America. Sci. Rep. 9, 8173. https://doi.org/10.1038/s41598-019-44614-4.

Garnelo, L., 2019. Especificidades e desafios das políticas públicas de saúde na Amazônia. Cad. Saúde Pública 35. https://doi.org/10.1590/0102-311x00220519.

Gasparrini, A., Armstrong, B., 2013. Reducing and meta-analysing estimates from distributed lag non-linear models. BMC Med. Res. Methodol. 13, 1. https://doi.org/10.1186/1471-2288-13-1.

Gasparrini, A., Armstrong, B., Kenward, M.G., 2012. Multivariate meta-analysis for non-linear and other multi-parameter associations. Stat. Med. 31, 3821–3839. https://doi.org/10.1002/sim.5471.

Gasparrini, A., Armstrong, B., Kenward, M.G., 2010. Distributed lag non-linear models. Stat. Med. 29, 2224–2234. https://doi.org/10.1002/sim.3940.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M.L., Guo, Y.L.L., Wu, C.F., Kan, H., Yi, S.M., De Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Honda, Y., Kim, H., Armstrong, B., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386, 369–375. https://doi.org/10.1016/S0140-6736(14)62114-0.

Green, H., Bailey, J., Schwarz, L., Vanos, J., Ebi, K., Benmarhnia, T., 2019. Impact of heat on mortality and morbidity in low and middle income countries: a review of the epidemiological evidence and considerations for future research. Environ. Res. 171, 80–91. https://doi.org/10.1016/j.envres.2019.01.010.

Guo, Y., Gasparrini, A., Armstrong, B.G., Tawatsupa, B., Tobias, A., Lavigne, E., De Sousa Zanotti Stagliorio Coelho, M., Pan, X., Kim, H., Hashizume, M., Honda, Y., Leon Guo, Y.L., Wu, C.F., Zanobetti, A., Schwartz, J.D., Bell, M.L., Scortichini, M., Michelozzi, P., Punnasiri, K., Li, S., Tian, L., Garcia, S.D.O., Seposo, X., Overcenco, A., Zeka, A., Goodman, P., Dang, T.N., Van Dung, D., Mayvaneh, F., Saldiva, P.H.N., Williams, G., Tong, S., 2017. Heat wave and mortality: a multicountry, multicommunity study. Environ. Health Perspect. 125 https://doi.org/10.1289/EHP1026.

Guo, Y., Gasparrini, A., Li, S., Sera, F., Vicedo-Cabrera, A.M., de Sousa Zanotti Stagliorio Coelho, M., Saldiva, P.H.N., Lavigne, E., Tawatsupa, B., Punnasiri, K., Overcenco, A., Correa, P.M., Ortega, N.V., Kan, H., Osorio, S., Jaakkola, J.J.K., Ryti, N.R.I., Goodman, P.G., Zeka, A., Michelozzi, P., Scortichini, M., Hashizume, M., Honda, Y., Seposo, X., Kim, H., Tobias, A., Íñiguez, C., Forsberg, B., Åström, D.O., Guo, Y.L., Chen, B.Y., Zanobetti, A., Schwartz, J., Dang, T.N., Van, D. Do, Bell, M.L., Armstrong, B., Ebi, K.L., Tong, S., 2018. Quantifying excess deaths related to heatwaves under climate change scenarios: a multicountry time series modelling study. PLoS Med. 15, 1–17. https://doi.org/10.1371/journal.pmed.1002629.

Hanna, E., Tait, P., 2015. Limitations to thermoregulation and acclimatization challenge human adaptation to global warming. Int. J. Environ. Res. Publ. Health 12, 8034–8074. https://doi.org/10.3390/ijerph120708034.

Hope, M., 2019. The Brazilian development agenda driving Amazon devastation. Lancet Planet. Health 3, e409–e411. https://doi.org/10.1016/S2542-5196(19)30195-0.

IBGE, n.d. Instituto Brasileiro de Geografia e Estatística [WWW Document]. Amaz. Leg. URL https://www.ibge.gov.br/geociencias/cartas-e-mapas/mapas-regionais/15819-amazonia-legal.html (accessed 5.11.22).

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Summary for Policymakers.

Janes, H., Sheppard, L., Lumley, T., 2005. Case crossover analyses of air pollution exposure data: referent selection strategies and their implications for bias. Epidemiology 16, 717–726. https://doi.org/10.1097/01.ede.0000181315.18836.9d.

Kenney, W.L., Craighead, D.H., Alexander, L.M., 2014. Heat waves, aging, and human cardiovascular health. Med. Sci. Sports Exerc. 46, 1891–1899. https://doi.org/10.1249/MSS.0000000000000325.

Lee, M., Shi, L., Zanobetti, A., Schwartz, J.D., 2016. Study on the association between ambient temperature and mortality using spatially resolved exposure data. Environ. Res. 151, 610–617. https://doi.org/10.1016/j.envres.2016.08.029.

Li, M., Gu, S., Bi, P., Yang, J., Liu, Q., 2015. Heat waves and morbidity: current knowledge and further direction-a comprehensive literature review. Int. J. Environ. Res. Publ. Health 12, 5256–5283. https://doi.org/10.3390/ijerph120505256.

Liu, C., Yavar, Z., Sun, Q., 2015. Cardiovascular response to thermoregulatory challenges. Am. J. Physiol. Heart Circ. Physiol. 309, H1793–H1812. https://doi.org/10.1152/ajpheart.00199.2015.

Maclure, M., 1991. The case-crossover design: a method for studying transient effects on the risk of acute events. Am. J. Epidemiol. 133, 144–153.

Marengo, J.A., Souza, C.M., Thonicke, K., Burton, C., Halladay, K., Betts, R.A., Alves, L. M., Soares, W.R., 2018. Changes in climate and land use over the Amazon region: current and future variability and trends. Front. Earth Sci. 6, 1–21. https://doi.org/10.3389/feart.2018.00228.

Mistry, M.N., Schneider, R., Masselot, P., Royé, D., Armstrong, B., Kyselý, J., Orru, H., Sera, F., Tong, S., Lavigne, É., Urban, A., Madureira, J., García-León, D., Ibarreta, D., Ciscar, J.-C., Feyen, L., de Schrijver, E., de Sousa Zanotti Stagliorio Coelho, M., Pascal, M., Tobias, A., Alahmad, B., Abrutzky, R., Saldiva, P.H.N., Correa, P.M., Orteg, N.V., Kan, H., Osorio, S., Indermitte, E., Jaakkola, J.J.K., Ryti, N., Schneider, A., Huber, V., Katsouyanni, K., Analitis, A., Entezari, A., Mayvaneh, F., Michelozzi, P., De'Donato, F., Hashizume, M., Kim, Y., Diaz, M.H., De la Cruz Valencia, C., Overcenco, A., Houthuijs, D., Ameling, C., Rao, S., Seposo, X., Nunes, B., Holobaca, I.-H., Kim, H., Lee, W., Íñiguez, C., Forsberg, B., Åström, C., Ragettli, M.S., Guo, Y.-L.L., Chen, B.-Y., Colistro, V., Zanobetti, A., Schwartz, J., Dang, T.N., Van Dung, D., Guo, Y., Vicedo-Cabrera, A.M., Gasparrini, A., 2022. Comparison of weather station and climate reanalysis data for modelling temperature-related mortality. Sci. Rep. 12, 5178. https://doi.org/10.1038/s41598-022-09049-4.

de Moraes, S.L., Almendra, R., Barrozo, L.V., 2022. Impact of heat waves and cold spells on cause-specific mortality in the city of São Paulo, Brazil. Int. J. Hyg Environ. Health 239, 113861. https://doi.org/10.1016/j.ijheh.2021.113861.

Qin, Y., Xiao, X., Wigneron, J.-P., Ciais, P., Brandt, M., Fan, L., Li, X., Crowell, S., Wu, X., Doughty, R., Zhang, Y., Liu, F., Sitch, S., Moore, B., 2021. Carbon loss from forest degradation exceeds that from deforestation in the Brazilian Amazon. Nat. Clim. Change 11, 442–448. https://doi.org/10.1038/s41558-021-01026-5.

Romanello, M., McGushin, A., Di Napoli, C., Drummond, P., Hughes, N., Jamart, L., Kennard, H., Lampard, P., Solano Rodriguez, B., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Chu, L., Ciampi, L., Dalin, C., Dasandi, N., Dasgupta, S., Davies, M., Dominguez-Salas, P., Dubrow, R., Ebi, K.L., Eckelman, M., Ekins, P., Escobar, L.E., Georgeson, L., Grace, D., Graham, H., Gunther, S.H., Hartinger, S., He, K., Heaviside, C., Hess, J., Hsu, S.-C., Jankin, S., Jimenez, M.P., Kelman, I., Kiesewetter, G., Kinney, P.L., Kjellstrom, T., Kniveton, D., Lee, J.K.W., Lemke, B., Liu, Y., Liu, Z., Lott, M., Lowe, R., Martinez-Urtaza, J., Maslin, M., McAllister, L., McMichael, C., Mi, Z., Milner, J., Minor, K., Mohajeri, N., Moradi-Lakeh, M., Morrissey, K., Munzert, S., Murray, K.A., Neville, T., Nilsson, M., Obradovich, N., Sewe, M.O., Oreszczyn, T., Otto, M., Owfi, F., Pearman, O., Pencheon, D., Rabbaniha, M., Robinson, E., Rocklöv, J., Salas, R.N., Semenza, J.C., Sherman, J., Shi, L., Springmann, M., Tabatabaei, M., Taylor, J., Trinanes, J., Shumake-Guillemot, J., Vu, B., Wagner, F., Wilkinson, P., Winning, M., Yglesias, M., Zhang, S., Gong, P., Montgomery, H., Costello, A., Hamilton, I., 2021. The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future. Lancet 398, 1619–1662. https://doi.org/10.1016/S0140-6736(21)01787-6.

Sanderson, M., Arbuthnott, K., Kovats, S., Hajat, S., Falloon, P., 2017. The use of climate information to estimate future mortality from high ambient temperature: a systematic literature review. PLoS One 12, e0180369. https://doi.org/10.1371/journal.pone.0180369.

Silveira, I.H., Cortes, T.R., Oliveira, B.F.A., Junger, W.L., 2020. Temperature and cardiovascular mortality in Rio de Janeiro, Brazil: effect modification by individual-level and neighbourhood-level factors. J. Epidemiol. Community Health, 215002. https://doi.org/10.1136/jech-2020-215002 jech-2020.

Silveira, I.H., Oliveira, B.F.A., Cortes, T.R., Junger, W.L., 2019. The effect of ambient temperature on cardiovascular mortality in 27 Brazilian cities. Sci. Total Environ. 691, 996–1004. https://doi.org/10.1016/j.scitotenv.2019.06.493.

Son, J.-Y., Liu, J.C., Bell, M.L., 2019. Temperature-related mortality: a systematic review and investigation of effect modifiers. Environ. Res. Lett. 14, 073004 https://doi.org/10.1088/1748-9326/ab1cdb.

Son, J.Y., Gouveia, N., Bravo, M.a., de Freitas, C.U., Bell, M.L., 2016. The impact of temperature on mortality in a subtropical city: effects of cold, heat, and heat waves in São Paulo, Brazil. Int. J. Biometeorol. 60, 113–121. https://doi.org/10.1007/s00484-015-1009-7.

Song, X., Wang, S., Hu, Y., Yue, M., Zhang, T., Liu, Y., Tian, J., Shang, K., 2017. Impact of ambient temperature on morbidity and mortality: an overview of reviews. Sci. Total Environ. 586, 241–254. https://doi.org/10.1016/j.scitotenv.2017.01.212.

Textor, J., Hardt, J., Knüppel, S., 2011. DAGitty. Epidemiology 22, 745. https://doi.org/10.1097/EDE.0b013e318225c2be.

Van den Wyngaert, I., De Troeyer, K., Vaes, B., Alsaiqali, M., Van Schaeybroeck, B., Hamdi, R., Casas Ruiz, L., Van Pottelbergh, G., 2021. Impact of heat waves on hospitalisation and mortality in nursing homes: a case-crossover study. Int. J. Environ. Res. Publ. Health 18, 10697. https://doi.org/10.3390/ijerph182010697.

Viana, R.L., de Freitas, C.M., Giatti, L.L., 2016. Saúde ambiental e desenvolvimento na Amazônia legal: indicadores socioeconômicos, ambientais e sanitários, desafios e perspectivas. Saúde e Soc. 25, 233–246. https://doi.org/10.1590/S0104-12902016140843.

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Coleman, S., Dalin, C., Daly, M., Dasandi, N., Dasgupta, S., Davies, M., Di Napoli, C., Dominguez-Salas, P., Drummond, P., Dubrow, R., Ebi, K.L., Eckelman, M., Ekins, P., Escobar, L.E., Georgeson, L., Golder, S., Grace, D., Graham, H., Haggar, P., Hamilton, I., Hartinger, S., Hess, J., Hsu, S.-C., Hughes, N., Jankin Mikhaylov, S., Jimenez, M.P., Kelman, I., Kennard, H., Kiesewetter, G., Kinney, P.L., Kjellstrom, T., Kniveton, D., Lampard, P., Lemke, B., Liu, Y., Liu, Z., Lott, M., Lowe, R., Martinez-Urtaza, J., Maslin, M., McAllister, L., McGushin, A., McMichael, C., Milner, J., Moradi-Lakeh, M., Morrissey, K., Munzert, S., Murray, K.A., Neville, T., Nilsson, M., Sewe, M.O., Oreszczyn, T., Otto, M., Owfi, F., Pearman, O., Pencheon, D., Quinn, R., Rabbaniha, M., Robinson, E., Rocklöv, J., Romanello, M., Semenza, J.C., Sherman, J., Shi, L., Springmann, M., Tabatabaei, M., Taylor, J., Triñanes, J., Shumake-Guillemot, J., Vu, B., Wilkinson, P., Winning, M., Gong, P., Montgomery, H., Costello, A., 2021. The 2020 report of the Lancet Countdown on health and climate change: responding to converging crises. Lancet 397, 129–170. https://doi.org/10.1016/S0140-6736(20)32290-X.

WMO, W.H.O., 2015. Heatwaves and Health: Guidance on Warning-System Development (Geneva, Switzerland).

Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., Tong, S., 2016. Impact of heatwave on mortality under different heatwave definitions: a systematic review and meta-analysis. Environ. Int. 89–90, 193–203. https://doi.org/10.1016/j.envint.2016.02.007.

Yang, J., Yin, P., Sun, J., Wang, B., Zhou, M., Li, M., Tong, S., Meng, B., Guo, Y., Liu, Q., 2019. Heatwave and mortality in 31 major Chinese cities: definition, vulnerability and implications. Sci. Total Environ. 649, 695–702. https://doi.org/10.1016/j.scitotenv.2018.08.332.

Yglesias-González, M., Palmeiro-Silva, Y., Sergeeva, M., Cortés, S., Hurtado-Epstein, A., Buss, D.F., Hartinger, S.M., 2022. Code Red for Health response in Latin America and the Caribbean: enhancing peoples' health through climate action. Lancet Reg. Heal. - Am., 100248 https://doi.org/10.1016/j.lana.2022.100248.

Yin, P., Chen, R., Wang, L., Liu, C., Niu, Y., Wang, W., Jiang, Y., Liu, Y., Liu, J., Qi, J., You, J., Zhou, M., Kan, H., 2018. The added effects of heatwaves on cause-specific mortality: a nationwide analysis in 272 Chinese cities. Environ. Int. 121, 898–905. https://doi.org/10.1016/j.envint.2018.10.016.

Zhou, M.G., Wang, L.J., Liu, T., Zhang, Y.H., Lin, H.L., Luo, Y., Xiao, J.P., Zeng, W.L., Zhang, Y.W., Wang, X.F., Gu, X., Rutherford, S., Chu, C., Ma, W.J., 2014. Health impact of the 2008 cold spell on mortality in subtropical China: the climate and health impact national assessment study (CHINAs). Environ. Health 13, 60. https://doi.org/10.1186/1476-069X-13-60.

Zuo, J., Pullen, S., Palmer, J., Bennetts, H., Chileshe, N., Ma, T., 2015. Impacts of heat waves and corresponding measures: a review. J. Clean. Prod. 92, 1–12. https://doi.org/10.1016/j.jclepro.2014.12.078.