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Air Pollution and Heat Waves

Heat wave characteristics, mortality and effect modification by temperature zones: a time-series study in 130 counties of China

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Abstract

Background: The substantial disease burden attributed to heat waves, and their increasing frequency and intensity due to climate change, highlight the importance of understanding the health consequences of heat waves. We explore the mortality risk due to heat wave characteristics, including the timing in the seasons, the day of the heat wave, the intensity and the duration, and the modifying effect of temperature zones.

Methods: Heat waves were defined as $\geq$ 2 days with a temperature $\geq$99th percentile for the county from 1 May through 30 September. Heat waves were characterized by their intensity, duration, timing in the season, and day of the heat wave. Within each county, we estimated the total non-accidental death and cardiovascular disease mortality during each heat wave compared with non-heat wave days by controlling for potential confounders in summer. We combined individual heat wave effect estimates using a random-effects model to calculate overall effects at the temperature zone and national levels.

Results: The average daily total number of non-accidental deaths was nine in the warm season (across all the counties). Approximately half of the daily total number of non-accidental deaths were cardiovascular-related deaths (approximately four persons per day). The average and maximum temperatures across the study area were 23.1 °C (range: -1.2–35.9 °C) and 28.3 °C (range: 5.4–42.8 °C), respectively. The average relative humidity during the study was 68.9% (range: 8.0–100.0%). Heat waves increase the risk of total non-accidental death by 15.7% [95% confidence interval (CI): 12.5, 18.9] compared with non-heat wave periods, and the risk of cardiovascular-related death increases by 22.0% (95% CI: 16.9, 27.4). The risk of non-accidental death during the first heat wave of the season increases by 16.3% (95% CI: 12.6, 20.2), the risk during the second heat wave increases by 6.3% (95% CI: 2.8, 9.9) and during subsequent heat waves increases by -2.1% (95% CI: -4.6, 0.4). The first day and the second to third days of heat waves increase the risk of total non-accidental death by 11.7% (95% CI: 7.6, 15.9) and 17.0% (95% CI: 13.1, 21.0), respectively. Effects of heat waves on mortality lasted more than 4 days (6.3%, 95% CI: 2.4, 10.5) and are non-significantly different from the first day of heat waves. We found non-significant differences of the heat wave-associated mortality risks across mid-, warm and subtropical temperature zones.

Conclusions: In China, the effect of heat waves on mortality is acute, and varies by certain characteristics of heat waves. Given these results, national heat wave early warning systems should be developed, as well as precautions and protection warranted according to characteristics of heat waves.

Key words: Heat waves, mortality, cardiovascular disease, temperature zone

Key Messages

- Based on extensive studies on the mortality risks due to heat waves, a relatively complete early warning system for heat waves has been established in developed countries. However, in developing countries such as China, few studies have explored the relations between mortality risks and heat wave characteristics.
- Using a time-series design, we showed that heat waves increase the risk of total non-accidental death by 15.7% (95% CI: 12.5, 18.9) compared with non-heat wave periods, and the risk of cardiovascular-related death increases by 22.0% (95% CI: 16.9, 27.4).
- Heat waves occurring earlier in the season potentially result in a greater mortality risk, especially effects associated with the first heat wave, which is nearly twice in effect size as the second one.
- Effects associated with longer durations of heat waves on mortality lasted for more than 4 days and were non-significantly different from those of the first day.

Introduction

Heat waves have become a major public health burden worldwide in the past few decades.[1] Many devastating heat waves have led to substantial public health consequences, such as the 1987 Athens heat wave, the 1995 Chicago heat wave, the 2003 European heat wave and the 2011 Sydney heat wave.[2–5] One of the most devastating heat waves, the 2003 European heat wave, affected many countries and caused over 70 000 deaths.[4,6] Given the severe global health burden associated with heat waves and a projection of an increasing frequency and intensity of heat waves due to climate change,[7] a better understanding of the health effects of heat waves, particularly the potential effects of heat wave characteristics, is needed.

Based on extensive studies examining the mortality risk due to heat waves, a relatively complete early warning system for heat waves has been established in developed countries.[8–10] However, although the frequency of heat waves is expected to increase by the end of the 21st century in developing countries such as China, few studies have explored the mortality risk associated with heat waves.[11–16] In part due to its vast territory and large latitude span, the thermal conditions in China vary widely across regions.[17] Spatial differences in the health effects of heat waves on the population have been observed, and temperature zones are gradually receiving attention as climate-related partitions.[11,15] The following six temperature zones are identified in China, according to the different accumulated temperatures of $\geq$10°C: a cold temperature zone, mid-temperature zone, warm temperature zone, subtropical zone, tropical zone and special Qinghai-Tibet alpine zone (Supplementary Table S1 and Supplementary Figure S1, available as Supplementary data at *IJE* online). Thus, the health effects of heat waves will likely differ across temperature zones in China.

Researchers generally agree that compared with non-heat wave days, the increasing health effects on heat wave days vary across studies using different definitions for heat waves.[18–20] The most widely used definitions for heat waves are characterized by the duration and intensity of heat waves, such as the occurrence of mean temperatures ≥95th (97.5th or 99th) percentile for ≥2 days.[10] However, in addition to the duration and the intensity of heat waves, other heat wave characteristics, the timing in the season and the day of the heat wave, can affect the health risk, as reported in several studies.[12,21–23] For example, one study in 43 US communities revealed a 2.49% increase in the heat wave-associated mortality risk for every 1- °F increase in heat wave intensity, and a 0.38% increase for every 1-day increase in heat wave duration; the mortality rate increased 5.04% [95% confidence interval (CI): 3.06, 7.06] during the first heat wave of the summer and 2.65% (95% CI: 1.14, 4.18) during later heat waves compared with non-heat wave days.[21] Cardiovascular disease-related health risk is susceptible to high temperatures.[24–26] In China, 290 million patients are diagnosed with cardiovascular diseases, and the mortality rate of cardiovascular diseases remained the highest in 2016. This disease burden will increase in the context of global warming.[27] Therefore, cardiovascular disease is one of the most important diseases to consider in public health. Based on available health outcomes, this study explores the potential effects of heat wave characteristics on non-accidental death and cardiovascular disease mortality risks.

This study explored the effects of heat wave characteristics, including the timing of heat waves in seasons, the day of the heat waves, the intensity of heat waves and the duration of heat waves, on mortality in the summer of 2013–15 in 130 counties across China. We also compared the effects of heat wave characteristics on individuals residing in different temperature zones.

Methods

Data

We collected daily county-level meteorological, mortality and fine particulate matter ($PM_{2.5}$) data from 1 January 2013, to 31 December 2015 for 130 counties in China. Meteorological data were obtained from the China Meteorological Data Sharing Service System [http://data.cma.cn/] and the China Meteorological Administration, including daily maximum temperature, daily 24-h mean temperature and daily 24-h mean relative humidity. The matching method for meteorological data requires each county to match the data obtained from the meteorological monitoring station within the county. Since counties are located within cities in China, we obtained the meteorological data for any county without a monitoring station from the station located in the city in which that county is located. We obtained daily mortality data for residents from the China Short-term Health Effects of Air Pollution (SHEAP) database, including daily total non-accidental mortality [ICD (International Classification of Diseases)-10: A00-R99] and cardiovascular mortality (ICD-10: I00-I99). We also collected daily 24-h mean $PM_{2.5}$ concentrations from the Department of Environmental Health at Emory University in the USA. Daily average concentrations of $PM_{2.5}$ were simulated for each 10-km*10-km grid across China, based on remote sensing satellites and a ground-based monitoring dataset. This dataset has been used in several published papers and the quality has been confirmed.[21–22] The data quality requirements are designed to ensure that the meteorological data, the death data and the $PM_{2.5}$ data are valid for more than 1000 days.

The specific method for selecting counties is described below. Among the 605 cause-of-death monitoring stations in the country, the counties with national environmental monitoring stations were selected, and of all counties that meet these rules, counties with an average mortality rate greater than 0.45% in 2013–15 and annual mortality volatility less than 20% were selected. If the annual mortality rate did not meet the requirements, the counties with the highest average mortality rate in the province or municipality in 2013–15 were selected as the study area, and finally each province or municipality was matched to at least two counties.

Definition of a heat wave

We analysed the mortality risk due to heat wave characteristics. We identified heat waves as ≥2 consecutive days with daily mean temperatures (T_{mean}) exceeding the county's 99th percentile of the T_{mean} during our study period. Heat wave characteristics include the timing in the season (i.e. the first heat wave of the year), the day of a heat wave (1 represents the first day of the heat wave), the duration of a heat wave (i.e. the number of days in a single heat wave) and the intensity of a heat wave (the daily maximum temperature). We limited the analysis to the warm season (1 May-30 September).

Statistical analysis

We examined the associations between heat waves and mortality using a two-stage approach. In the first stage, we fitted a generalized linear model (GLM) with a quasi-Poisson distribution to separately estimate the mortality risk associated with exposure to heat waves for each county (Model a):

$$Log\ (\mu_{t,i}) = \beta_{0,i} + \beta_1 HW_{t,i} + ns\ (rh_{t,i},\ df) + \beta_2 DOW_{t,i} + ns\ (time_{t,i},\ df)\ model\ a$$

where $\mu_{t,\ I}$ = expected number of deaths for county i on day t; $HW = 0$ if day t is a non-heat wave day and 1 if day t is a heat wave day. The natural cubic spline was three degrees of freedom (*df*) for the potential confounder of relative humidity (*rh*); the days of the week (*DOW*) was an indicator variable that controlled for variations among the days of the week. A natural cubic spline of *time* with two *df* per season was used to exclude long-term and seasonal trends in mortality.

We added the timing of the heat wave, a categorical variable, in the season to the model (Model b) to further explore the effects of the heat wave characteristics on the association between heat waves and mortality:

$$Log\ (\mu_{t,i}) = \beta_{0,i} + \beta_1 HW_{t,i+} ns\ (rh_{t,i},\ df) + \beta_2 DOW_{t,i} + ns\ (time_{t,i},\ df)\ model\ b$$

where $HW = 0$ if day t is a non-heat wave day, 1 if day t is the first heat wave in a year, 2 if day t is the second heat wave in a year, and 3 if day t is the third or higher heat wave in the year.

We added the day of the heat wave, a categorical variable, to the model (model c) to further explore the effects of heat wave characteristics on mortality:

$$Log\ (\mu_{t,i}) = \beta_{0,i} + \beta_1 HWD_{t,i} + ns\ (rh_{t,i},\ df) + \beta_3 DOW_{t,i} + ns\ (time_{t,i},\ df)\ model\ c$$

where $HWD = 0$ if day t is a non-heat wave day, 1 if day t is the first day of any heat wave, 2 if day t is the second to third day of any heat wave and 3 if day t is more than the third day of the heat wave.

In the second stage, we performed a random-effects univariate meta-analysis by pooling the coefficients in the first stage to examine the associations between the heat waves and mortality in different temperature zones (see additional details in Supplementary Table S1 and Supplementary Figure S1) and the whole country. We also estimated the pooled mortality risk for heat wave characteristics, including the timing in the season and the day of the heat wave. A meta-regression was used to test the statistical difference between effect estimates for different timings of the heat wave (Model b), different days of the heat wave (Model c) and different temperature zones.[28–30] The relative risk (RR) obtained for different timings of the season, days of the heat wave and temperature zones were compared using the Wald test implemented in the meta-regression model.[28–30] We further conducted a univariate meta-analysis and a multivariate meta-analysis to explore explanations (population, economic level, age structure and sex ratio) for the heterogeneity in the effects of heat waves on different counties. We used the restricted maximum likelihood method in the meta-analysis to obtain unbiased variance estimates.

Sensitivity analysis

We conducted a sensitivity analysis to test the robustness of our methods. First, we fitted a variety of specifications to Model a that was used in the primary analysis, including: (i) different lag days (Supplementary Table S3, available as Supplementary data at *IJE* online) and different heat wave definitions (Supplementary Table S4, available as Supplementary data at *IJE* online); (ii) separate adjustments for the same-day maximum temperature, heat wave duration or daily concentration of $PM_{2.5}$ (Supplementary Table S5, available as Supplementary data at *IJE* online); and (iii) different *df* for the spline functions (Supplementary Table S5). Then, for Models b and c, we also examined the sensitivity of the estimates to the *df* used in the spline functions (Supplementary Tables S6 and S7, available as Supplementary data at *IJE* online).

All analyses were performed using R statistical software (version 3.3.1). We used the 'mvmeta' package in the second stage of the analysis.

Results

During our study period, 530 681 non-accidental deaths were observed across the 130 counties, with 237 443 deaths due to cardiovascular disease. The 130 counties are shown in Figure 1. Figure 1 shows the maximum temperature, average temperature, number of heat waves and duration of the longest heat wave in each county. The warm season in the south-eastern coastal areas is relatively hotter than in the inland and north-east regions. The highest daily maximum and average temperatures were observed in Meilan, and the lowest values were observed in Jinchuan. However, relatively high frequencies of heat waves were observed in the roughly coastal areas and northern China, followed by some counties in the north-east and south-west, and relatively few heat waves occur in the north-west and south-east. Similarly, heat waves in the coastal and south-east regions lasted longer than in other areas.

We calculated summary statistics related to daily cause-specific deaths, meteorological data and $PM_{2.5}$ data in the warm season from 2013 to 2015 across the 130 counties (Table 1). The average daily total number of non-accidental deaths in the warm season was nine, with five males and four females. On average, five deaths were observed among adults aged 75 and older, a value that is more

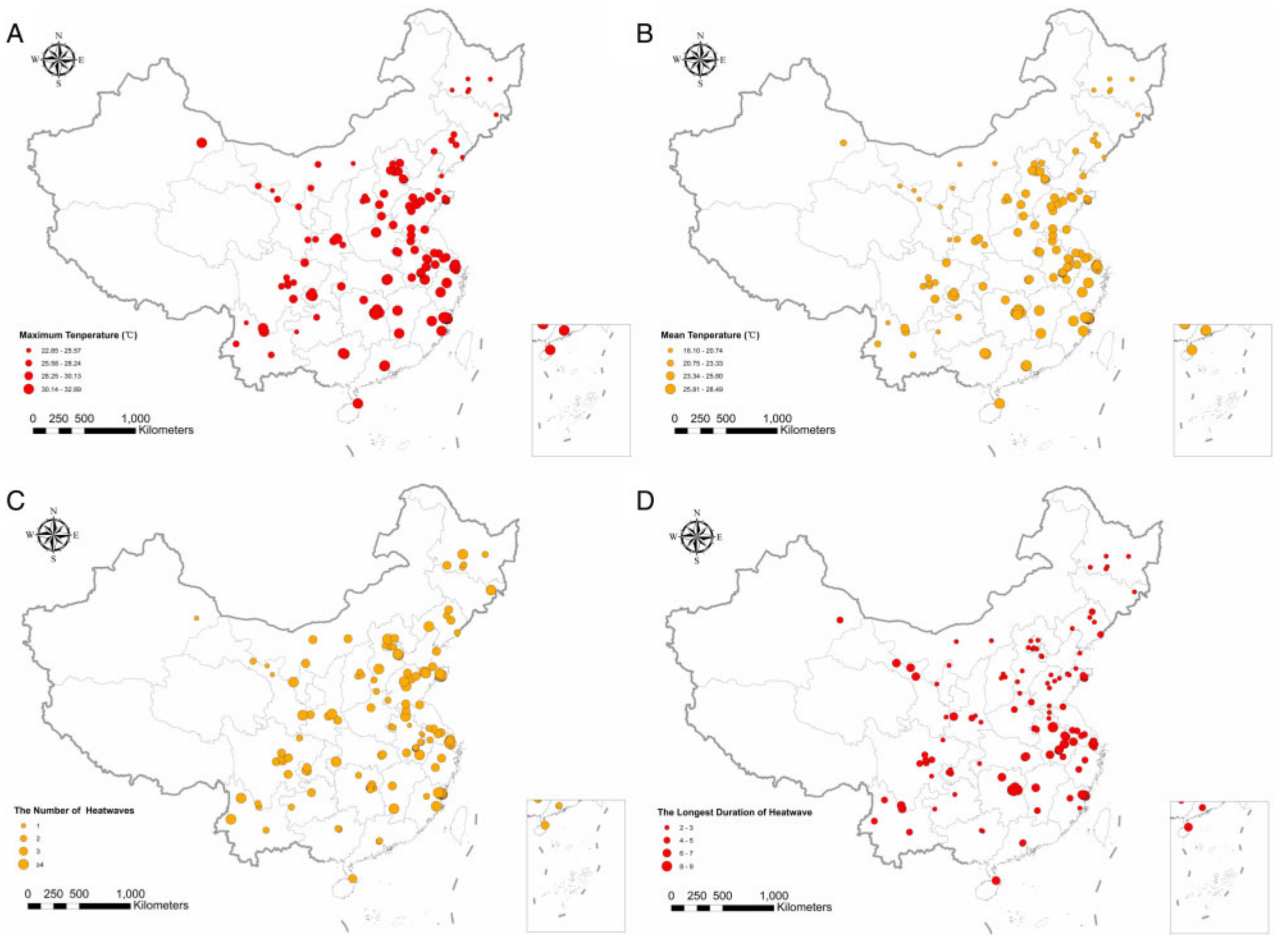

Figure 1. Characteristics of heat waves in the 130 counties of China from 2013 to 2015. A: Average daily maximum temperature. B: average daily mean temperature. C: number of heat waves. D: duration of the longest heat wave.

Table 1. Descriptive statistics for daily mortality and meteorological variables

	No. of days	Mean	Stdev	Minimum	P25[a]	P50[a]	P75[a]	Maximum
Total non-accidental deaths	495	9	6	0	4	8	12	68
Male	495	5	4	0	2	4	7	34
Female	495	4	3	0	2	3	6	34
0-64 years old	495	2	2	0	1	2	3	16
65-74 years old	495	2	2	0	1	1	3	18
>75 years old	495	5	4	0	2	4	7	51
Cardiovascular diseases	495	4	3	0	2	3	5	46
Mean temperature (°C)	491	23.1	5.1	−1.2	20.1	23.5	26.6	35.9
Maximum temperature (°C)	495	28.3	5.1	5.4	25.1	28.7	32.0	42.8
Mean relative humidity (%)	484	68.9	16.8	8.0	59.0	72.0	81.0	100.0

Stdev, standard deviation.
[a]P25: 25th percentile; P50: 50th percentile; P75: 75th percentile.

than double the average number of deaths in the younger age groups. The average number of deaths during the warm season in each county is shown in Supplementary Table S8, available as Supplementary data at *IJE* online. The average number of daily deaths in 12 counties was fewer than four, and the average number of daily cardiovascular disease deaths in all 50 counties was fewer than four. The average and maximum temperatures during the study period were 23.1 °C and 28.3 °C, respectively.

Across the 130 counties, the mortality risks were substantially increased during heat waves, with an increase of 15.7% (95% CI: 12.5, 18.9) for non-accidental deaths and

Table 2. Percent increase (95% CI) in mortality risk due to heat waves in 130 counties

Heat wave		Total non-accidental mortality		Cardiovascular mortality	
		% increase (95% CI)	***P***[b]	% increase (95% CI)	***P***[b]
Model a[a]	Heat wave	15.65 (12.47, 18.92)	/	22.02 (16.91, 27.35)	/
Model b[a]	The first heat wave	16.30 (12.58, 20.15)	Ref	23.83 (18.17, 29.77)	Ref
	The second heat wave	6.28 (2.76, 9.92)	$P<0.05$	9.73 (3.76, 16.05)	$P<0.05$
	Additional heat waves	−2.14 (-4.60, 0.38)	$P<0.05$	−0.03 (-4.02, -4.12)	$P<0.05$
Model c[a]	The 1st day of the heat wave	11.67 (7.58, 15.92)	Ref	15.38 (8.83, 22.33)	Ref
	The 2nd-3rd days of the heat wave	16.95 (13.07, 20.96)	$P>0.05$	24.26 (18.15, 30.68)	$P>0.05$
	The 4th and subsequent days of the heat wave	6.34 (2.35, 10.49)	$P<0.05$	12.01 (5.69, 18.70)	$P>0.05$

[a]Model a: percent increase (95% CI) in the mortality risk associated with heat waves across the 130 counties.

Model b: percent increase (95% CI) in the mortality risk associated with the timing of the heat wave in the season across the 130 counties.

Model c: percent increase (95% CI) in the mortality risk associated with the day of the heat wave across the 130 counties.

[b]The Wald test *P*-values are the mortality risk of the second heat wave vs the first heat wave (Model b), additional heat waves vs the first heat wave (Model b), the 2nd-3rd days of the heat wave vs the 1st day of the heat wave, and the 4th and subsequent days of the heat wave vs the 1st day of the heat wave.

Table 3. Percent increase (95% CI) in mortality risks associated with heat waves in the 130 counties in the areas analysed using Model a

Heat wave	Total non-accidental mortality		Cardiovascular mortality	
	% increase (95% CI)	***P***[a]	% increase (95% CI)	***P***[a]
Mid-temperature zone	18.17 (11.35, 25.41)	Ref	19.86 (10.32, 30.23)	Ref
Warm temperature zone	17.61 (11.65, 23.89)	$P>0.05$	23.87 (14.59, 33.91)	$P>0.05$
Subtropical temperature zone	13.55 (9.38, 17.88)	$P>0.05$	20.67 (13.46, 28.34)	$P>0.05$

[a]The Wald test *P*-value of the coefficients comparing warm temperate zone vs the medium temperature zone and of the subtropical zone vs the medium temperature zone.

22.0% (95% CI: 16.9, 27.4) for cardiovascular-related deaths compared with non-heat wave periods (Table 2). The results of the meta-regression analysis did not reveal a significant decrease in heterogeneity, and the results of the multivariate meta-analysis were not significantly different from the original results (Supplementary Table S2, available as Supplementary data at *IJE* online). We observed a significant effect of the timing in the season on the heat wave-mortality associations. The first heat wave in the season was associated with the greatest mortality risk [16.3% (95% CI: 12.6, 20.2) for non-accidental mortality], and the risks decreased substantially for the second (6.3%) and the subsequent heat waves (-2.1%). Thus, early heat waves are associated with a greater mortality risk than later waves. A similar pattern in risks was observed for cardiovascular-related mortality.

The effect sizes of the first day, and second to third days, of the heat wave on total non-accidental and cardiovascular mortality appeared to be larger than that of the fourth and subsequent days of the heat wave (Table 2). However, the differences across exposure groups, using the effect of the first day as the reference, were not statistically significant ($P>0.05$). The second to third days of the heat wave increased the associated mortality risk for total non-accidental deaths by 17.0% (95% CI: 13.1, 21.0) and for cardiovascular deaths by 24.3% (95% CI: 18.2, 30.7), the 95% CI: of which overlapped with that of other days although having the highest effect estimates.

Tables 3–5 show the results for the heat wave-related mortality risks in different temperature zones. Because no counties are located in the cold temperature zone, and less than four counties are located in the plateau climatic zone and the tropics, those three temperature zones were not included in the meta-analysis. The risk of non-accidental death due to heat waves in Model a increased by 18.2% (95% CI: 11.4, 25.4), 17.6% (95% CI: 11.7, 23.9), and 13.6% (95% CI: 9.4, 17.9) in the mid-temperature zone, warm temperature zone and subtropical zone, respectively, and the risk of cardiovascular disease-related death increased by 19.9% (95% CI: 10.3, 30.2), 23.9% (95% CI: 14.6, 33.9) and 20.7% (95% CI: 13.5, 28.3), respectively (Table 3). As shown in Table 4, the point estimates of the first heat wave on both non-accidental and cardiovascular disease-related deaths were larger than those of subsequent events, among which residents of the mid-temperature zone were affected the most, followed by residents of the warm temperature zone and the subtropical temperature zone. However, there was no substantial difference across

Table 4. Percent increase (95% CI) in mortality risks associated with the timing of the heat wave in the season in the 130 counties in the areas analysed in using Model b

The timing of the heat wave in the season	Total non-accidental mortality		Cardiovascular mortality	
	% increase (95% CI)	P^a	% increase (95% CI)	P^a
The first heat wave				
Mid-temperature zone	20.72 (13.38, 28.55)	Ref	23.65 (13.28, 34.97)	Ref
Warm temperature zone	16.56 (9.42, 24.17)	$P > 0.05$	22.67 (12.51, 33.75)	$P > 0.05$
Subtropical temperature zone	14.42 (9.70, 19.34)	$P > 0.05$	24.84 (16.45, 33.83)	$P > 0.05$
The second heat wave				
Mid-temperature zone	−3.86 (−8.42, 0.91)	Ref	−4.04 (−10.60, 3.01)	Ref
Warm temperature zone	11.62 (4.23, 19.53)	$P > 0.05$	17.86 (6.10, 30.92)	$P > 0.05$
Subtropical temperature zone	8.55 (3.55, 13.79)	$P > 0.05$	12.13 (3.16, 21.87)	$P > 0.05$
The third and successive heat waves				
Mid-temperature zone	−10.15 (−15.72, -4.21)	Ref	−10.06 (−17.94, -1.43)	Ref
Warm temperature zone	−1.79 (−5.92, 2.52)	$P > 0.05$	−1.45 (−7.26, 4.73)	$P > 0.05$
Subtropical temperature zone	−0.06 (−3.64, 3.65)	$P > 0.05$	4.91 (−1.68, 11.94)	$P > 0.05$

[a]The Wald test *P*-value of the coefficients comparing warm temperate zone vs the medium temperature zone and of the subtropical zone vs the medium temperature zone.

Table 5. Percent increase (95% CI) in mortality risks for the day of the heat wave in the 130 counties

The day in the heat wave	Total non-accidental mortality		Cardiovascular mortality	
	% increase (95% CI)	P^a	% increase (95% CI)	P^a
The 1st day of the heat wave				
Mid-temperature zone	16.50 (6.11, 27.91)	Ref	19.78 (5.29, 36.28)	Ref
Warm temperature zone	13.26 (6.09, 20.91)	$P > 0.05$	16.25 (4.81, 28.94)	$P > 0.05$
Subtropical temperature zone	8.15 (2.49, 4.13)	$P > 0.05$	11.59 (2.68, 21.28)	$P < 0.05$
The 2nd-3rd days of the heat wave				
Mid-temperature zone	19.39 (10.56, 28.93)	Ref	19.29 (6.99, 33.00)	Ref
Warm temperature zone	19.62 (12.56, 27.13)	$P > 0.05$	27.98 (17.32, 39.60)	$P > 0.05$
Subtropical temperature zone	14.29 (9.03,19.81)	$P > 0.05$	22.54 (13.77, 31.99)	$P > 0.05$
The 4th and subsequent days of the heat wave				
Mid-temperature zone	−5.56 (-9.22, -1.74)	Ref	−4.28 (-10.19, 2.03)	Ref
Warm temperature zone	6.74 (-0.03, 13.96)	$P > 0.05$	8.17 (-0.78, 17.93)	$P > 0.05$
Subtropical temperature zone	13.95 (6.89, 21.47)	$P > 0.05$	27.77 (15.73, 41.06)	$P > 0.05$

[a]The Wald test *P*-value of the coefficients comparing warm temperate zone vs the medium temperature zone and of the subtropical zone vs the medium temperature zone.

the timing of the heat wave by geographical location ($P > 0.05$). As shown in Table 5, on the first day of the heat wave, the greatest point-estimate of heat waves was observed on mortality risks in the mid-temperature zone, followed by the warm temperature zone and the subtropical zone. On the second to third days of the heat wave, the greatest estimate was found in the warm temperature zone, whereas in addition to the fourth and subsequent heat wave days, the greatest point-estimate of heat waves was observed in the subtropical temperature zone. Notably this phenomenon, differential effects of day of the heat wave by geographical location, was not confirmed by the statistical test.

Supplementary Tables S3–S7 show the results of the sensitivity analysis. The lag analysis results indicate that the mortality risk of heat waves was immediate (Supplementary Table S3, available as Supplementary data at *IJE* online). At the same time, the heat wave results were verified using different heat wave definitions, and the following definition better reflected the effect of heat waves on the human body: temperatures greater than the 99th percentile for two consecutive days. After changing the definition of heat waves, the greatest effect of heat waves was observed using this definition in the present study (Supplementary Table S4). After including the maximum temperature in Model a, the mortality risk due to heat waves decreased, and the risk of total non-accidental deaths decreased from 15.7% (95% CI: 12.5, 18.9) to 11.9% (95% CI: 8.6, 15.2) (Supplementary Table S5). After including the duration of the heat waves in Model a, the risk of heat wave-associated mortality increased, and the risk of total non-accidental deaths rose from 15.7% (95% CI: 12.5, 18.9) to 17.0% (95% CI: 12.8, 21.4) (Supplementary Table S5). After controlling for $PM_{2.5}$ pollution in Model a, the effect of heat waves on death was slightly reduced (Supplementary Table S5). After changing the *df* of the relative humidity and time in Model a, the effect of heat waves on mortality exhibited little change, and thus the model displayed good stability (Supplementary Table S5). After changing the *df* of the relative humidity and time in Models b and c, the effect of heat waves on death changed very little, and therefore the models displayed good stability (Supplementary Tables S5–S7).

Discussion

To the best of our knowledge, this study is currently the largest investigation of the associations between heat wave characteristics and mortality risk. Our results add important findings to the existing evidence for the health impacts of exposure to heat waves. First, heat waves are associated with community-wide increases in total non-accidental and cardiovascular disease-related mortality risks. Second, heat waves occurring earlier in warm seasons may pose greater threats to humans. Moreover, the effects of heat waves on mortality lasted more than 4 days and are non-significantly different from the first day of heat waves. We have not, however, found sufficient evidence to support the hypothesis that the heat wave-associated mortality risks and risks modified by certain heat-wave characteristics differ across temperature zones. Based on this evidence and a high incidence trends in heat waves, a heat wave early warning system nationwide must be implemented in China, and precautions should be announced according to characteristics of heat wave risks, with a particular focus on early events.

We observed evidence of an increased effect of heat waves on total non-accidental mortality, which is somewhat consistent with the findings of previous studies. During the 2001 heat wave, the mortality risk in Moscow was increased by 33% (95% CI: 20–46).[31] Although the effect estimates [15.7% (95% CI: 12.5, 18.9)] in this study are much smaller than the Moscow estimates, they are larger than in other studies conducted in the USA, Europe and South Korea.[20,22,32] For example, a time-series study of 43 communities in the USA during the period 1987–2005 reported a 3.7% (95% CI: 2.3, 5.2) increase in all-cause mortality during a heat wave compared with non-heat wave days.[20] The difference in mortality risk due to heat waves may be related to the characteristics of heat waves, the health status of the study population, and the socioeconomic status of the study population.[10,20] In China, some single-location studies have also been conducted to explore the effects of heat waves on mortality, and the effects reported in these single-centre studies are greater than our results.[32–34] Heat waves were associated with a 24.6% increase (95% CI: 15.6, 34.3) in total mortality in Nanjing.[32] After including multiple locations, the pooled effect of heat waves decreased. The risk associated with heat waves increased by 8.2% (95% CI: 3.4, 13.2) in four cities of China.[12] Therefore, the difference in the results from single- and multicentre studies indicates that the results of research conducted in different locations cannot be generalized, and more centralized studies should be conducted to develop targeted early warning systems.

The effect size of heat waves on mortality was more pronounced for cardiovascular disease-related mortality, similar to the results of previous studies.[11,32] Cardiovascular disease-related death was recently shown to be more sensitive to temperature.[24–26,35] Some hypotheses have been proposed. For example, increased temperature may lead to faster blood flow and higher blood pressure, resulting in a decreased oxygen supply and a higher risk of cardiovascular disease-related death.[36] Compared with the study conducted in Nanjing, which indicated that heat waves are associated with a 46.9% increase (95% CI: 33.0, 62.3) in cardiovascular disease-associated mortality and 51.3% increase (95% CI: 23.4, 85.6) in mortality due to strokes, our study identified a smaller risk [22.0% (95% CI: 16.9, 27.4].[32] However, individual studies have not observed significant effects of heat waves on cardiovascular disease-related mortality.[12,19] Because the frequency and intensity of heat waves will increase in the future, targeted heat wave warnings must be provided for individuals with heat-sensitive diseases, such as cardiovascular diseases.[7]

Some characteristics of heat wave may modify the heat wave-related mortality risk. Our study shows that heat waves emerging early in the warm season can have a greater effect on mortality, which is consistent with the results of some previous studies.[20] Potential explanations for this finding include body condition of adaptation, air conditioning usage and staying indoors to prevent exposure to high temperatures after the start of the heat wave.[37] The relationship between early heat waves and mortality risk may be more pronounced because of the harvesting effect of heat waves.[6] The vulnerable population has already died in earlier heat waves. Thus, the government should specify targeted early warnings for heat waves to properly allocate health resources. As shown in the present study, the effects of heat waves on mortality lasted more than 4 days, which indicated that heat waves with a longer duration may be more harmful than those with shorter duration.[21] Our results showed that there was no significant difference in the heat wave-associated mortality risks between the first day and subsequent days of the heat wave, similar to the findings of Zeng *et al*.,[12] and suggests that adverse influences of the late phase of heat waves also need to be closely monitored.

Some studies showed that the relationships between heat waves and mortality risks may also be modified by location.[11,15,21,39] A previous study conducted in 66 communities in China showed a greater mortality effect of heat waves in North China, followed by East China and South China.[11] From a geographical perspective, a higher mortality risk for heat waves in the northern region than in other regions is potentially due to long-term physiological and behavioural adaptations of the local people.[39] We have not found sufficient evidence to support the hypothesis that the heat wave-associated mortality risks and risks modified by certain heat-wave characteristics differ across mid-, warm and subtropical temperature zones. It may indicate that the independent modification of geographical factors on heat wave-associated risks cannot be observed well by the regional stratification of these climate zones, which is mixed with economic and demographic factors and population health and adaptation. Further analyses of geographical modification of heat wave-associated risks need to be conducted nationwide.

Not only is this study the largest research investigating the relationship between heat waves and mortality in China, but it also explores the mortality risk associated with heat wave characteristics, such as the seasonal timing of the heat wave and the day of the heat wave. Moreover, this study further explored the effect of heat wave characteristics in different temperature zones after considering the temperature distribution characteristics in China.

This study still had some limitations. First, ambient air pollutants are potential confounders of the association between heat waves and mortality.[40–41] Based on the available data, we only adjusted for the possible confounding effect of $PM_{2.5}$ in this study and did not control for other air pollutants. Second, the effect of heat waves on mortality may be related to the use of air conditioning.[40–42] Our study did not control for the confounding effects of air conditioning because we were unable to obtain air conditioning data from each county. Third, in our study: the 3-year time-series data were analysed using the generalized linear model; the time-series may not be long enough; and the nonlinear relationship between heat waves and mortality was not considered. Due to the small number of daily deaths in some counties during the time-series, the *P*-value among the temperature zones may be less significant.

Future studies should further explore the effects of other pollutants on the relationship between heat waves and mortality, and we recommend that subsequent studies should control for the effects of air conditioning. At the same time, we hope that future studies will investigate longer and newer time-series and verify whether a nonlinear relationship exists between heat waves and mortality. Future studies should also analyse additional health outcomes and provide more evidence to support policy development.

In conclusion, as shown in the present study, heat waves increase the risks of non-accidental deaths and cardiovascular disease-related deaths. Characteristics of heat waves, including intensity levels and duration as well as timing, play important roles in heat wave-associated mortality risks. Based on these findings, heat-wave early warning systems nationwide, along with precautions announced according to characteristics of heat wave risk, are necessary, which would substantially reduce the burden of heat wave-related deaths in China.

Supplementary data

Supplementary data are available at *IJE* online.

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Author contributions

T.L. made contributions to the concept and design of the study. Z.S., C.C., Z.D., W.S., J.W., J.B. and Q.S. collected the data, Z.S. and C.C. performed the statistical analysis and drafted the article. All authors contributed to interpreting the results and revised the draft critically.

Conflict of interest

None declared.

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