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The short-term effect of heat waves on mortality and its modifiers in China: An analysis from 66 communities

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A B S T R A C T

Background: Many studies have reported increased mortality risk associated with heat waves. However, few have assessed the health impacts at a nation scale in a developing country. This study examines the mortality effects of heat waves in China and explores whether the effects are modified by individual-level and community-level characteristics.
Methods: Daily mortality and meteorological variables from 66 Chinese communities were collected for the period 2006–2011. Heat waves were defined as ≥2 consecutive days with mean temperature ≥95th percentile of the year-round community-specific distribution. The community-specific mortality effects of heat waves were first estimated using a Distributed Lag Non-linear Model (DLNM), adjusting for potential confounders. To investigate effect modification by individual characteristics (age, gender, cause of death, education level or place of death), separate DLNM models were further fitted. Potential effect modification by community characteristics was examined using a meta-regression analysis.
Results: A total of 5.0% (95% confidence intervals (CI): 2.9%–7.2%) excess deaths were associated with heat waves in 66 Chinese communities, with the highest excess deaths in north China (6.0%, 95% CI: 1%–11.3%), followed by east China (5.2%, 95% CI: 0.4%–10.2%) and south China (4.5%, 95% CI: 1.4%–7.6%). Our results indicate that individual characteristics significantly modified heat waves effects in China, with greater effects on cardiovascular mortality, cerebrovascular mortality, respiratory mortality, the elderly, females, the population dying outside of a hospital and those with a higher education attainment. Heat wave mortality effects were also more pronounced for those living in urban cities or densely populated communities.
Conclusion: Heat waves significantly increased mortality risk in China with apparent spatial heterogeneity, which was modified by some individual-level and community-level factors. Our findings suggest adaptation plans that target vulnerable populations in susceptible communities during heat wave events should be developed to reduce health risks.

1. Introduction

Numerous studies have demonstrated that heat waves are associated with increased mortality (Anderson and Bell, 2011; Huynen et al., 2001; Le Tertre et al., 2006; Ostro et al., 2009; Son et al., 2012). Some of these studies also reported that individual characteristics modified the association between heat waves and mortality (Lin et al., 2011; Medina-Ramón et al., 2006; Son et al., 2012). For instance, a study conducted in seven U.S. cities found that age, gender and cause of death significantly modified the heat effects on mortality (O'Neill et al., 2003); and studies from Guangdong province and Shanghai city of China showed that heat wave effects were higher for respiratory mortality and the elderly ≥75 years old (Ma et al., 2012; Zeng et al., 2014).

Some multi-city studies have also reported that the mortality effects of heat-wave were spatially heterogeneous, which may be partially explained by city-level modifiers such as socio-economic status and adaptive capacity (Curriero et al., 2002; Reid et al., 2009). For example, in the United States, one study revealed a greater increase in heat-related

Abbreviations: AIC, Akaike information criterion; AC, air conditioning; CI, confidence interval; CBD, cerebrovascular disease; CER, cumulative excess risk; CVD, cardiovascular disease; GDP, Gross Domestic Product; HW, heat wave; IQR, inter-quartile range; PM_{10}, particulate matter with aerodynamic diameters less than 10 μm; RESP, respiratory disease.

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mortality for a low socio-economic population compared with a high socio-economic population (O'Neill et al., 2003). Another study showed people living in urban areas were more vulnerable possibly due to the urban heat island effect and greater social isolation (Laaidi et al., 2012; Tan et al., 2009). O'Neill and colleagues found that central air-conditioning (AC) prevalence could explain some of the differences in heat effects by race (O'Neill et al., 2005).

Although many previous studies have investigated the mortality risk of heat waves, most studies focused on a single city or a small number of cities because of limited data availability, and these studies used different methods and parameter specifications making it difficult to compare the results from different studies (Guo et al., 2011; Sun et al., 2014; Tan et al., 2006; Wang et al., 2014). Furthermore, few previous studies considered the potential modifiers of heat wave effects on mortality (Ma et al., 2012), which are helpful to identify those populations and regions more vulnerable to heat waves. A more comprehensive understanding of the relationship between heat waves and mortality is important in developing policies and strategies that specifically target the most vulnerable populations and regions during heat wave events.

In the past five decades, especially in the first decade of the 21st century, the frequency and intensity of heat waves increased significantly in China (IPCC, 2013; Kan et al., 2012). Though some studies have examined mortality risk associated with high temperature (Lin et al., 2011; Ma et al., 2012; Wang et al., 2014), no research has comprehensively assessed the mortality effects of heat waves across the diverse climatic regions of China.

In the present study, we estimated the mortality effects of heat waves during summer in the years 2006–2011 using data from 66 Chinese communities, and further identified individual-level and community-level factors that confer susceptibility to heat waves. Our study aims to provide information for policy makers and the public to better understand the health effects of heat waves in China.

2. Methods

2.1. Study sites

China, located in East Asia and with a large coastline on the Pacific Ocean, covers an area of 9.6 million square kilometers. China's Disease Surveillance Points system (DSPs) is a set of 161 communities (each community is a county or a district of a city), chosen to be nationally representative. The system is administrated by the Chinese Center for Disease Control and Prevention (China CDC) (Zhou et al., 2010). The DSPs record all deaths and population counts at the sites and yields a nationally representative annual sample of deaths (Yang et al., 2005; Zhou et al., 2010). In order to assure enough daily death counts for every surveillance point in model fitting for time series analysis, the current study only included 66 DSPs where the population size is over 200 000. The Huai River-Qin Mountains Line was used as the geographical dividing line between north and south China. East and west China were defined according to the Chinese Government official classification. The selected 66 communities are distributed across four geographical regions: East China (16 communities in Jiangsu, Zhejiang, Anhui and Shanghai), South China (17 communities in Hubei, Hunan, Jiangxi, Fujian, Guangdong and Guangxi), West China (15 communities in Shanxi, Gansu, Ningxia, Xinjiang, Qinghai, Sichuan, Guizhou, Yunnan and Chongqing) and North China (18 communities in Heilongjiang, Liaoning, Jilin, Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia and Henan) (Supplementary Fig. A1). The 66 DSPs are home to 44.3 million inhabitants (Supplementary Fig. A1, Table A1).

2.2. Data collection

2.2.1. Mortality data

For each community, mortality data during the warm season (May 1–September 30) from 2006 to 2011 were obtained from China CDC (Gasparrini and Armstrong, 2011). In China, the CDC is the government agency responsible for health data collection and a death must be reported to the local CDC. The hospital or community/village doctors filled in a standard Death Certificate and the information was then reported to a higher administrative level of CDC through a network reporting system. The standard information collected individual-level information, such as cause of death, date of death, age, gender and education attainment. In this study, we classified the deaths according to the International Classification of Diseases (ICD-10) for external causes (A00-R99), cardiovascular diseases (CVD: I00-I99), cerebrovascular diseases (CBD: I60-I69) and respiratory diseases (RESP: J00-J99). We also divided daily deaths into several strata by gender, place of death (in hospital or outside hospital), age groups (0–64 years, 65–74 years and 75 years or older) and education attainment (low: <6 years of education, medium: 6–9 years of education and high: >9 years of education). The place of death was defined as "in hospital", which included a hospital, clinic, or medical center, as well as outpatients admitted to the emergency room; and "outside hospital", including all other deaths, such as deaths at home.

2.2.2. Meteorological data

Daily meteorological data from all communities were collected from the China Meteorological Administration Network, a compilation of quality-controlled global surface observations, including daily mean temperature, daily maximum temperature, daily minimum temperature and daily relative humidity. Diurnal temperature range was calculated as the difference between maximum and minimum temperatures within 1 day for the community during the study period.

2.2.3. Community level data

Community level data were collected from the sixth national census, including marital status, percentage of unemployed population, per capita GDP, latitude, population size, ownership of air-conditioning per 100 households and urbanization, which have been commonly used as indicators of socio-economic status (Curriero et al., 2002; Zeng et al., 2014). We collected air pollution data (PM_{10}) from 55 communities: 26 community data sets were obtained from the local environmental protection agency website; 12 community data sets were collected from literature reviews and government reports, and for another 17 communities without specific data, we used data from the nearby communities. All the community level variables were shown in Table 1.

2.3. Statistical analysis

2.3.1. The definition of heat wave

To date, there has been no consistent definition of heat wave. In China, heat wave is defined as a period of at least 3 days where daily maximum temperature exceeds 35 °C (Tan et al., 2006). However, several studies have indicated that it may not be appropriate to use a unique temperature as a threshold in a spatially large country (Anderson and Bell, 2009; Kent et al., 2014). In the present study, we defined a heat wave as ≥ 2 consecutive days with daily mean temperature at or above the 95th percentile of the year-round community-specific distribution (Gasparrini and Armstrong, 2011) (Supplementary Table A1). Heat wave was classified as a dichotomous variable with 1 for heat wave days and 0 for non-heat wave days.

2.3.2. Analysis of heat wave effects on mortality

The statistical analysis followed an approach already proposed for several multicity studies (Lin et al., 2011; Wu et al., 2013). We first applied a Distributed Lag Non-linear Model (DLNM) to each community and then combined the estimates using a meta-analysis (Gasparrini et al., 2010; Lin et al., 2011). We also explored whether effect estimates differ by region to understand spatial distribution of heat wave effects on mortality. To examine the cumulative excess mortality risks (CERs, %) with heat wave at a 0–1 day lag, we fitted the following Poisson

Table 1
The characteristics of community-level variables in 66 communities of China.

Variable	Description (source)	Mean	IQR[a]	Minimum, maximum
Marital situation				
Unmarried (%)	Percentage of those who are unmarried (2010 China Population Censuses)	21.12	6.75	11, 33
Married (%)	Percentage of those who are married (2010 China Population Censuses)	71.4	6.31	60.39, 71.4
Divorced (%)	Percentage of those who are divorced (2010 China Population Censuses)	1.7	1.23	0.64, 3.65
Unemployment (%)	Percentage of those aged 16 years who are unemployed (2010 China Population Censuses)	35	15.49	13.97, 57.35
GDP	Gross Regional Domestic Product for the community	3.74	3.04	0.21, 19.37
Latitude	Latitude for the community	33.14	7.88	21.27, 47.23
Population (NO.)	Total population (2010 China Population Censuses)	670,485	469,484	200,231,1,582,398
AC (unit)	Ownership number of AC per 100 households (2010 China Economic Census)	65	94	1, 212
Urban	Dichotomy variable with 1 for rural communities and 2 for urban cities.	–	–	–
PM_{10} levels (μg/m^3)	Average PM_{10} concentrations for the community for the study period (community-specific environmental website)	98.95	25.35	47.6, 327.0
Weather factors				
Temperature (°C)	Average temperature for the community for the study period (National Climatic Data Center)	23.43	4.85	15, 28.1
Diurnal Temperature range (°C)	the difference between maximal and minimal temperatures within 1 day for the community for the study period (National Climatic Data Center)	9.03	2.68	5.30, 14.2
Relative humidity (%)	Average relative humidity for the community for the study period (National Climatic Data Center)	70.19	7.65	39.8, 88.50

[a] IQR, inter-quartile range.

regression model for each community after adjusting for daily maximum temperature, relative humidity, time trends, day of the week and holidays for potential confounding factors:

$$Log\ E(Y_t) = \alpha + cb(HW_t,\ lag) + ns\left(T_{max},df = 3\right) + ns(Rh_t,\ df = 3) + ns(Time_t,\ df = 27) + \beta_1 Dow_t + \beta_2 Holiday_t \quad (1)$$

where Y_t refers to the number of deaths on day t; α is intercept; cb means "cross-basis" function; ns means the natural spline function; and df means degrees of freedom, chosen by the Akaike Information Criterion (AIC); HW_t refers to heat wave (HW) on day t, which is a binary variable assuming a value of 1 during the heat wave period, with lag equal to 1. We limited the maximum lag to 1 day, because our exploratory analysis indicated that the heat effect was acute and short, with the largest effect at lag 0–1 (Supplementary Fig. A2). We used 2 df for HW. T_{max} refers to the maximum temperature on day t, with 3 df; Rh_t refers to humidity on day t, with 3 df; $Time_t$ refers to the time variable to adjust for time trends, with 27 df; Dow_t is a categorical variable for day of the week, and β_1 is the coefficient; $Holiday_t$ is the binary variable indicating public holidays, and β_2 is the coefficient.

2.3.3. Effect modifiers of the heat wave–mortality relationship

To investigate effect modification by individual factors, we fitted separate DLNMs for each individual factor, such as gender, cause of death (CVD, CBD, RESP), age groups (0–64 years, 65–74 years and 75 years or older), places of death (at hospital or outside hospital) and education attainment (<6 years, 6–9 years and >9 years). Then we used a meta-analysis to pool the exposure-mortality effects among these subgroups.

We further used a mixed-effects meta-regression model to investigate effect modification of community-level factors (Lin et al., 2013a; Smith-Warner et al., 2006). Spearman's correlation coefficients were calculated between the 13 community-level variables, and some variables were highly correlated (r > 0.9) (Supplementary Table A2). So, firstly, each community level variable was included in the mixed-effect meta-regression model. Community level variables which significantly modified heat-wave-mortality associations were further explored in multivariate mixed-effects meta-regression model. The model can be described as follows:

$$\hat{\beta}^c = \alpha_0 + \sum\nolimits_j \alpha_{1,j} x_j^c + \varepsilon^c + U^c. \quad (2)$$

For c = 1, …. c, where c is the community number, the $\hat{\beta}^c$ are the estimated community-specific heat wave effects, α_0 is average log relative rate for average community, α_j means change in the log relative rate β^c for an inter-quartile increase in community-level variable x, x_j is the value of descriptor variable for community c (such as marital status), ε^c is the community-specific random effects, and U^c is the within-community sampling errors.

Results were presented as the percentage increase in daily mortality during heat wave days compared to non-heat wave days at lag 0–1 for an inter-quartile increase in the community level variables.

2.3.4. Sensitivity analysis

Sensitivity analyses were conducted by changing the df of time trends, with df (time) = 7, 8 and 9/year.

We used the "dlnm" package in R software version 3.0.1 (R Development Core Team, 2010) to derive the estimates. The meta-regression analytic techniques were performed using a random effects model in "metafor" package. We defined statistical significance at the 5% level.

3. Results

Table 2 shows the characteristics of 66 communities and heat waves during the summer periods (May–September) of 2006–2011. Among the four regions, south China had the highest daily mean temperature, and northeast China had the lowest daily mean temperature. Average daily humidity was similar across the four regions, ranging from 64.9% in north China to 75.2% in south China and east China. The temperature thresholds for heat waves across four regions were different; south China had the highest threshold, and northeast China had the lowest. The average number of heat waves during the study period was similar among the four geographical regions. The average intensity of heat wave (measured as average temperature during the heat wave periods) was higher in east and south China. Most heat waves lasted for 3 or 4 days and occurred in June, July or August.

Fig. 1 depicts the comparison of average daily death counts during heat wave and non-heat wave days for the 66 communities. Overall, the number of deaths on heat wave days was higher than that on non-heat wave days and this was consistently found for the individual characteristic groupings. The results were similar for the four regions of China (Supplementary Fig. A3).

Fig. 2 shows the spatial distribution of cumulative excess risks of heat wave on mortality at lag 0–1 in China. A total of 5.0% (95% CI: 2.9%–7.2%) excess deaths was caused by heat waves in 66 communities. The mortality risk was highest in north China (CER = 6.0%, 95% CI: 1%–11.3%), followed by east China (CER = 5.2%, 95% CI: 0.4%–10.2%), south

Table 2
Temperature, humidity and heat wave characteristics in 66 communities during summer (May–September) of 2006–2011, China, by region.

	East China	South China	West China	North China	Overall
Number of communities	16	17	15	18	66
Temperature (°C) [average (Min, Max)]					
Daily maximum temperature	24.3 (12.7,32.9)	26.9 (16.2,33)	22.1 (10.9,30.6)	21.6 (8.2,31.1)	23.4 (11.7,31.8)
Daily mean temperature	28.3 (14.6,37.8)	31.4 (18.3,38.9)	27.8 (13.4,38)	27.1 (11.7,38.3)	28.5 (14.2,38.2)
Daily minimum temperature	21.1 (8.9,29.3)	23.6 (13.9,29.6)	17.7 (7.2,25.8)	16.7 (3.5,26.6)	19.5 (7.9,27.6)
Humidity (%) [average (Min, Max)]	75.2 (32.3,98)	75.2 (40.4,97)	67.5 (31.1,96.5)	64.9 (16.8,96.1)	70.7 (29.3,96.8)
HW characteristics					
HW[a] Threshold (°C)	28.6	30.3	26.2	26.2	27.6
HW Frequency (average NO./year)	4.0	4.3	3.8	4.2	4.1
HW Intensity (average tm) (°C)	29.8	31.1	27.6	27.5	28.8
HW Duration (average days)	3.9	3.8	4.2	3.6	3.9

[a] HW: heat wave.

China (CER = 4.5%, 95% CI: 1.4%–7.6%) and west China (CER = 3.9%, 95% CI: −0.6%–8.7%).

Fig. 3 shows the heat-wave-related mortality risk by individual factors. We found that the estimated CER was higher for cardiovascular mortality (7.7%, 95% CI: 4.7%–10.7%) than for cerebrovascular mortality (6.2%, 95% CI: 1.9%–10.7%) and respiratory mortality (5.3%, 95% CI: 0.8%–10%). It was higher for the elderly over 75 years (6.1%, 95% CI: 3.2%–9.1%) compared with those less than 75 years old (4% (95% CI: 0.5%–7.6%) for 0–64 years old and 3.4% (95% CI: 0.1%–6.9%) for 65–74 years old), and for females (5.8%, 95% CI: 2.7%–9.1%) compared with males (4.0%, 95% CI: 1.6%–6.5%). The effects were more pronounced for those dying outside of hospital than those dying in hospital and for those with higher education attainment than for those with low education attainment. The results were similar for the four Chinese regions (Supplementary Fig. A4).

The results of modification effect by community level factors are shown in Table 3. People living in urban cities or densely populated communities had higher mortality risks compared with those living in rural areas. The estimated amount of residual heterogeneity is equal to $\tau^2 = 0.0014$, suggesting that 42.62% of the total amount of heterogeneity can be accounted for by including these two moderators in the model (urban cities and densely populated communities). However, there was no statistically significant difference in mortality risk for other community characteristics such as marital status, employment rate, PM_{10}, GDP, latitude and some weather factors. In the multivariate meta-regression model, we found a 2.64% increase in the slope (95% CI: 0.07%–5.28%) for every 469,484-person increase in population, and a 4.62% increase in the slope (95% CI: 0.69%–8.71%) for urban areas.

For the sensitivity analysis, all analyses were repeated by varying df of time trends per year to examine model robustness. The results were similar when time trends were set to 7/year or 8/year (Supplementary Table A3).

4. Discussion

The association between heat waves and mortality has been well documented in developed countries (Anderson and Bell, 2011; D'Ippoliti et al., 2010; Laaidi et al., 2012). However, understanding of spatial distribution of heat wave mortality risk and the role of the potential modifiers remains limited, particularly in developing countries. To our knowledge, this is the largest study to describe the spatial heterogeneity of heat wave mortality risk in China and the first study to comprehensively identify the modification effects by individual-level and community-level characteristics using data from 66 Chinese communities.

We found a positive association between heat wave and mortality, which is consistent with previous studies (Anderson and Bell, 2011; D'Ippoliti et al., 2010; Huang et al., 2010; Curriero et al., 2002). Moreover, our study showed that the morality risks of heat wave were spatially heterogeneous in China. There was a greater effect in north China, followed by east China and south China, implying that populations in north China were more susceptible to heat waves than those in south China. Previous studies explained this spatial heterogeneity by acclimatization from long-term physiological and behavioral adaptation (McGeehin and Mirabelli, 2001). This finding indicates that using an absolute temperature as the threshold for defining a heat wave in a

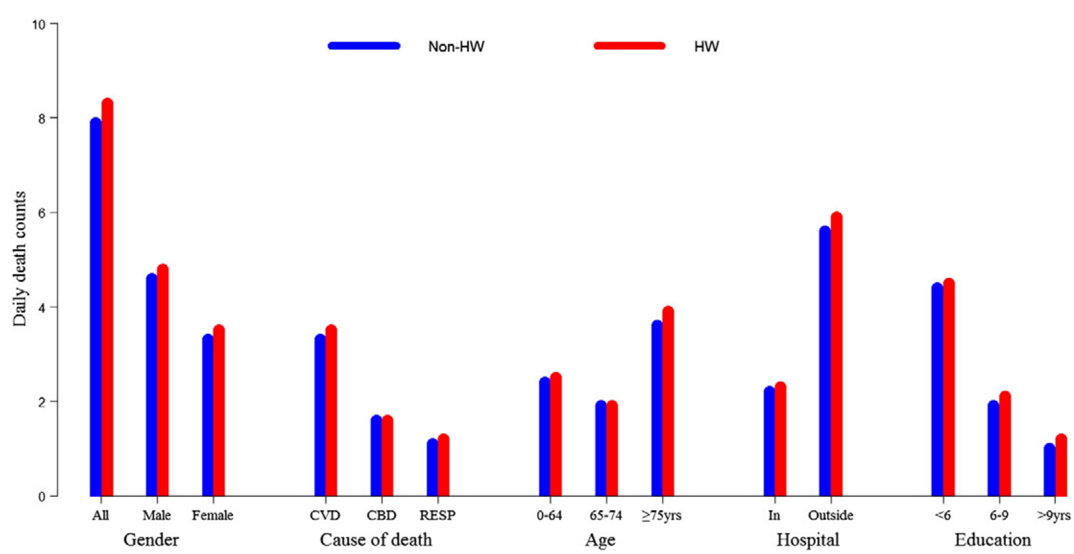

Fig. 1. Comparison of average daily mortality between heat wave (HW) and non-Heat wave (Non-HW) days by gender, cause of death, age group, place of death and education attainment in 66 communities, China.

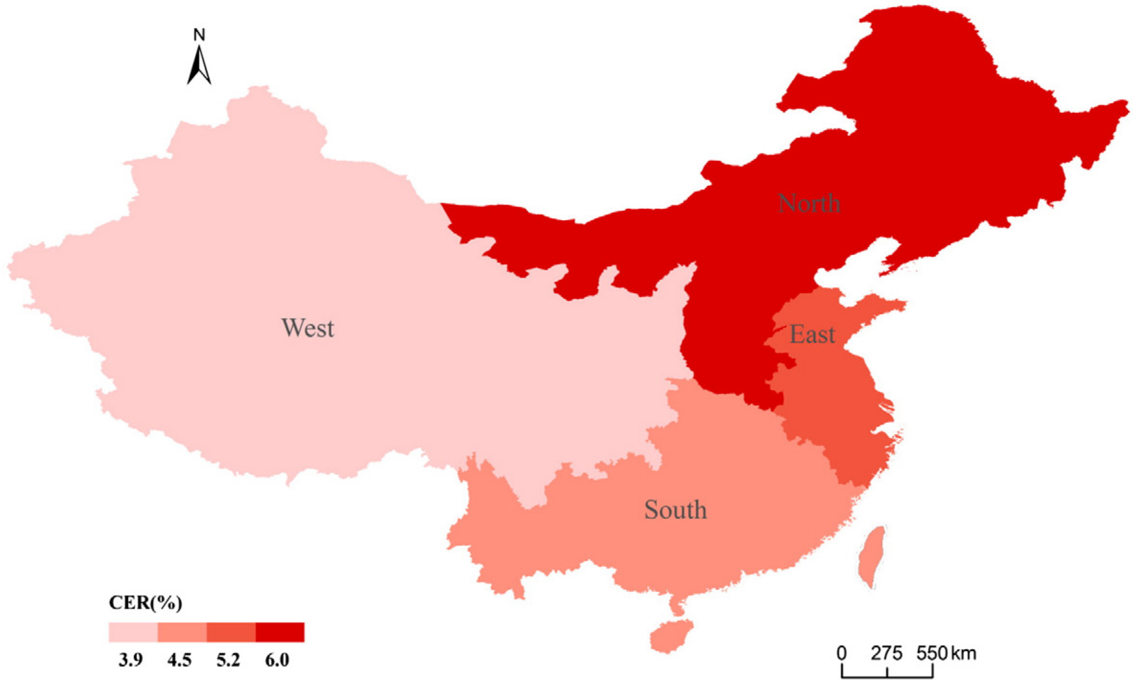

Fig. 2. Spatial distribution of cumulative excess risks (CERs, %) of heat waves on mortality at lag 0–1 across 4 regions of China.

large country like China may not be appropriate because populations in different regions have variable vulnerability to heat waves. Currently, heat wave is arbitrarily defined as a period of at least 3 days where daily maximum temperature exceeds 35 °C across China and findings here suggest that policymakers in China need to consider regional sensitivity to heat waves when developing regional specific response plans.

We further observed a greater effect of heat waves on cardiovascular mortality and respiratory mortality than total mortality, consistent with some previous studies (Ishigami et al., 2008; Le Tertre et al., 2006), indicating increased susceptibility among people suffering from chronic cardiovascular or respiratory diseases (D'Ippoliti et al., 2010). This may relate to the adaptation of a healthy peripheral circulation to environmental temperatures that occurs within a few minutes (Barnetta et al., 2007). We also found increased risk for the elderly. This may be due to reducing thermoregulatory capacity over time or taking some medicine which may interfere with the process of heat loss (Astrom et al., 2011). Another possibility is low risk perception and adaptation capacity to heat wave among the elderly. For instance, our previous study observed that the elderly in south China had very low health risk perception to heat wave and used fewer adaption measures during extreme heat events (Liu et al., 2013). This suggests that the mortality effects of heat wave may be even larger in the coming decades because the rapid aging trend in China will lead to a greater number of aging population and therefore designing adaptation plans for heat waves targeting these particularly vulnerable populations is an important and urgent task for public health.

The present study also found a higher mortality effect for those dying outside hospital compared with those dying in hospital. Some previous studies observed similar findings (Medina-Ramón et al., 2006; Son et al., 2012). This suggests that mortality risk may be affected by heat exposure levels because air filtration and air conditioning are different for populations inside and outside hospital. Death in a hospital may also reflect other socio-economic status difference such as health insurance and access to health care (O'Neill et al., 2003). The fact of

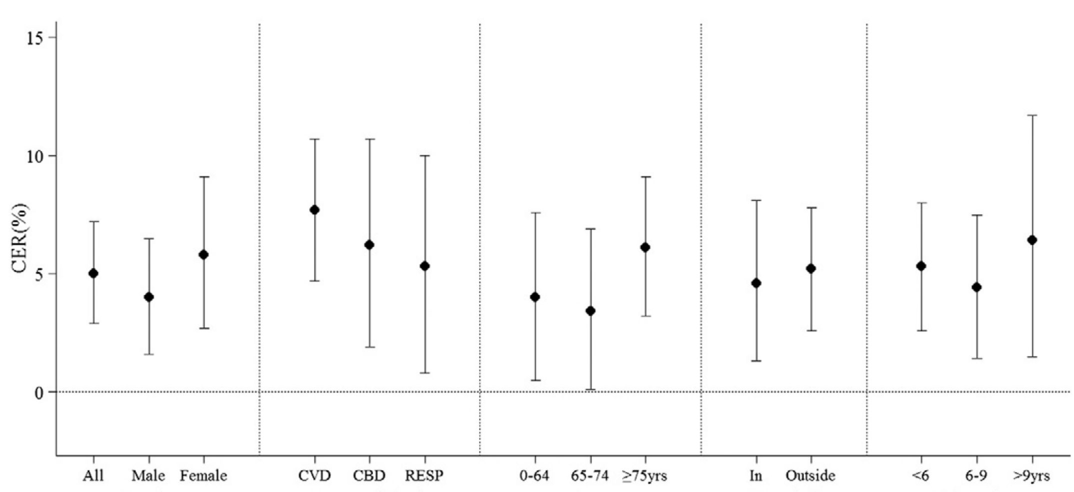

Fig. 3. Modification effects on heat wave mortality by individual characteristics in 66 communities of China. The points represent the excess risks, and the vertical lines represent 95% confidence intervals.

Table 3
Estimated percent change in the association between heat wave and mortality per IQR[a] increase in community-level predictors, China, 2006–2011.

Predictor	Percentage increase in mortality effect of heat wave per IQR increase in community variable				Heterogeneity parameter (τ^2)	Percentage of total variance due to between-study variance (%)
	IQR	Central estimate	95% CI[a]	P		
Single community-level predictor models						
Married situation (%)						
Unmarried	6.75	1.56	−1.36,4.56	0.30	0.00248	1.64
Married	6.31	−1.06	−3.86,1.82	0.47	0.00253	3.69
Devoiced	1.23	2.13	−0.99,5.34	0.18	0.00227	6.97
Unemployment	15.49	0.31	−2.53,3.23	0.84	0.00256	4.92
GDP[a]	3.04	0.75	−0.72,2.24	0.32	0.00247	1.23
Latitude	7.88	0.3	−2.3,2.97	0.82	0.00255	4.51
Population	469,484	2.97*	0.3,5.71	0.03	0.00186	23.77
AC (numbers of household owned)	93.79	2.41	−0.51,5.41	0.11	0.00229	6.15
Urban	–	5.11*	1.03,9.34	0.01	0.00186	23.77
PM_{10} (ug/m^3)[a]	25.35	−0.51	−2.17,1.17	0.55	0.00301	23.36
Weather						
Temperature (°C)	4.85	0.38	−3.13,4.02	0.83	0.00255	4.51
Diurnal Temperature range (°C)	2.68	0.5	−1.04,2.06	0.53	0.00244	0.00
Relative humidity (%)	7.65	0.97	−0.83,2.81	0.29	0.00242	0.82
Multivariate community-level predictor models						
Population	469,484	2.64*	0.07,5.28	0.04	0.00140	42.62
Urban	–	4.62*	0.69,8.71	0.02		

[a] IQR, inter-quartile range; CI, confidence interval; GDP, gross national income; PM_{10}, particulate matter with an aerodynamic diameter of ≤10 μm.
* $P < 0.05$.

social inequality in China calls for more attention to improving the healthcare provision and reforming the fiscal arrangement by governments so as to ensure more equitable health outcomes (Zhang and Kanbur, 2005). Surprisingly, populations with higher education were more vulnerable to heat wave in our study, which was in contrast to previous studies showing that people with low education attainment may be more vulnerable to heat waves (Liu et al., 2013). Further carefully designed research is needed to better understand the reasons for this result.

In the present study, we found that communities with greater vulnerability to heat wave were characterized by urban areas and higher population densities. This finding is similar with some previous studies (Goggins et al., 2012; Tan et al., 2009), suggesting that the presence of an urban heat island effect due to the thermal capacity of buildings and sealing surfaces with artificial materials may be an important potential modifier of heat effects. Heat is more efficiently retained throughout the night-time in urbanized areas. Lacking of temperature variability would be more likely to cause a failure of thermoregulation and result in heat-related mortality (Lin et al., 2013b; Luo et al., 2013). China is experiencing rapid urbanization with an urbanization ratio rising from around 20% in the early 1980s to 45% in 2007 (Rey et al., 2009). In light of the findings here and this rapid urbanization, it is very important for the government to improve city planning, design, construction and operation drawing on the research evidence on successful cooling strategies in urban areas from other city locations around the world to reduce this urban heat island effect and associated health impacts in the future.

It is well known that lack of air-conditioning (AC) might be associated with excess heat-related deaths (Medina-Ramon and Schwartz, 2007; Tan et al., 2006). However, the results in our study found that AC did not play an important role in the mortality effect of heat wave. Actually, one multi-city study found that central AC prevalence could explain some of the differences in heat effects, but room-unit AC did not (Zanobetti and Schwartz, 2005). Another cohort study showed that no real benefit was derived from room-unit AC (Rogot et al., 1992). Until now, most Chinese households are equipped with room-unit AC rather than central AC, and some vulnerable populations (such as the elderly) do not use AC due to high electricity cost (Liu et al., 2013). All the above reasons may explain why AC is not associated with mortality risk reduction in our study. Therefore, it's necessary for the government to improve the adaptation capacity of these vulnerable populations by recommending alternative measures, such as encouraging residents to remain in the coolest parts of the building as much as possible, to wear light, loose cotton clothes, or to regularly sprinkle cool water, and so on (Matthies and Menne, 2009).

Some limitations exist in this present study. Firstly, this study was not able to account for interactions between air pollution and high temperature because of data unavailability, although evidence of interaction between air pollution and high temperatures has been found in some urban areas during specific heat wave episodes (Katsouyanni et al., 1993; Qian et al., 2008; Ren et al., 2008). In addition, difference among community characteristics are likely to exist and can be present in smaller aggregated units, but we only collected data at district or county level in the present study.

5. Conclusions

Our study found a significant increase in mortality during heat waves in 66 Chinese communities with notable heterogeneity among communities, which is partially modified by some individual-level and community-level characteristics. Our findings suggest effective adaptation policies that target vulnerable populations, particularly the elderly and those with pre-existing diseases in susceptible communities during heat wave events should be developed to reduce health risks. Furthermore, such adaptation policies should be developed at a regional or even community level as sensitivity to heat waves is different across different regions of China.

Competing interests

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2014.11.004.

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