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Temperature modifies the acute effect of particulate air pollution on mortality in eight Chinese cities

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HIGHLIGHTS

► Few studies examine the interaction between temperature and PM_{10} on mortality.
► Extremely high temperature intensified the effects of PM_{10} in 8 Chinese cities.
► Our study has implications for both air pollution and global climate change.
► This is the first multi-city study of its kind in Asian developing region.

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ABSTRACT

Background: Both temperature and particulate air pollution are associated with increased death risk. However, whether the effect of particulate air pollution on mortality is modified by temperature remains unsettled.
Methods: A stratified time-series analysis was conducted to examine whether the effects of particulate matter less than 10 μm in aerodynamic diameter (PM_{10}) on mortality was modified by temperature in eight Chinese cities. Poisson regression models incorporating natural spline smoothing functions were used to adjust for long-term and seasonal trends of mortality, as well as other time-varying covariates. The bivariate response surface model was applied to visually examine the potential interacting effect. The associations between PM_{10} and mortality were stratified by temperature to examine effect modification.
Results: The averaged daily concentrations of PM_{10} in the eight Chinese cities ranged from 65 μg/m^3 to 124 μg/m^3, which were much higher than in Western countries. We found evidence that the effects of PM_{10} on mortality may depend on temperature. The eight-city combined analysis showed that on "normal" (5th–95th percentile) temperature days, a 10-μg/m^3 increment in PM_{10} corresponded to a 0.54% (95% CI, 0.39 to 0.69) increase of total mortality, 0.56% (95% CI, 0.36 to 0.76) increase of cardiovascular mortality, and 0.80% (95% CI, 0.64 to 0.96) increase of respiratory mortality. On high temperature (>95th percentile) days, the estimates increased to 1.35% (95% CI, 0.80 to 1.91) for total mortality, 1.57% (95% CI, 0.69 to 2.46) for cardiovascular mortality, and 1.79% (95% CI, 0.75 to 2.83) for respiratory mortality. We did not observe significant effect modification by extreme low temperature.
Conclusions: Extreme high temperature increased the associations of PM_{10} with daily mortality. These findings may have implication for the health impact associated with both air pollution and global climate change.

1. Introduction

China is one of the countries with exceptionally high particulate matter (PM) pollution in the world (Kan et al., 2009). Short-term exposure to PM has been linked to increased risk of mortality (Pope and Dockery, 2006). Temperature has long been recognized as a physical hazard, and is associated with a wide range of adverse health effects (Basu and Samet, 2002). Typically, a U-shaped relationship between temperature and daily mortality is observed with mortality risk decreasing from the lowest temperature to an inflection point and then increasing with higher temperature (Kan et al., 2003). The effect of temperature on mortality may be different in areas with different weather patterns, latitudes, air pollution levels and prevalence of air-conditioning systems (Basu and Samet, 2002).

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The rapid build-up of greenhouse gases is expected to increase not only mean temperature but also temperature variability. Extreme temperature has been associated with increased risks of mortality and morbidity (Huang et al., 2010; Ma et al., 2011). Recently, interest has been focused on the possible interacting effect of air pollution and extreme temperature (Carder et al., 2008; Katsouyanni et al., 1993; Li et al., 2011; Qian et al., 2008; Ren and Tong, 2006; Ren et al., 2006, 2008; Roberts, 2004; Stafoggia et al., 2008; Zanobetti and Schwartz, 2008). However, whether the health effect of air pollution is modified by temperature remains unsettled. For example, Samet et al. found little evidence that weather conditions modified the effect of pollution (Samet et al., 1998), while Ren et al. observed that temperature significantly modified the health effects of PM in Brisbane, Australia (Ren and Tong, 2006). Moreover, most of these studies were conducted in Australia, North America and Europe, and only a small number of studies have been conducted in China, the largest emitter of carbon dioxide (CO_2) in the world (Li et al., 2011; Qian et al., 2008). The need of such kinds of studies remains in Chinese cities, where characteristics of outdoor air pollution (e.g., air pollution level and mixture), meteorological conditions, and sociodemographic patterns of local residents may differ from those in Western countries.

In this study, we did a stratified time-series analysis to examine whether extreme temperature modified the effect of particulate matter less than 10 μm in aerodynamic diameter (PM_{10}) on daily mortality in eight Chinese cities. We considered PM_{10} because the current Chinese Air Quality Standard includes PM_{10} only among various PM metrics.

2. Methods

2.1. Data

The eight Chinese cities include Guangzhou, Hangzhou, Shanghai, Shenyang, Suzhou, Taiyuan, Tianjin, and Wuhan (Fig. 1). These cities have different geographic features and weather patterns. Three (Shenyang, Taiyuan and Tianjin) and five (Guangzhou, Hangzhou, Shanghai, Suzhou, and Wuhan) cities are located in the north and south part of China, respectively. Our study areas were restricted to the urban areas of these cities, due to inadequate air pollution monitoring stations in the suburban areas.

Daily mortality data of urban residents were obtained from the Municipal Center for Disease Control and Prevention in each city. The causes of death were coded according to the International Classification of Diseases, 10 (ICD-10). The mortality data were classified into deaths due to total non-accidental causes (ICD-10: A00-R99), cardiovascular disease (ICD-10: I00-I99), and respiratory disease (ICD-10: J00-J98).

The PM_{10} data were collected from the National Air Pollution Monitoring System (NAPMS) that were in the China National Quality Control for air monitoring network. The daily (24-h) average concentrations of PM_{10} were measured using the tapered element oscillating microbalance (TEOM) method. Chinese government has mandated detailed quality assurance and quality control programs at the NAPMS providing the PM_{10} data. For the calculation of 24-h mean concentrations, at least 75% of the one-hour values must be available on that particular day. If a station had more than 25% of the values missing for the whole period of analysis, the entire station was excluded from the analysis. The location of monitoring stations are mandated not to be in the direct vicinity of traffic or of industrial sources, and not to be influenced by local pollution sources and should also avoid buildings, or those that house large emitters such as coal-, waste-, or oil-burning boilers, furnaces, and incinerators. In each city, the daily PM_{10} concentrations were averaged from the available monitoring results across various stations.

Meteorological data (daily mean temperature and relative humidity) were provided by the National Meteorological Information Center (CMA) of China.

2.2. Statistical methods

Daily death, air pollution and weather data are linked by date and therefore were analyzed with a time-series design (Zeger et al., 2006). We used the generalized additive model (GAM) to analyze the daily mortality, PM_{10}, and temperature data. Because daily death numbers typically follow a Poisson distribution, the core analysis was a GAM with log link and Poisson error that accounted for smooth fluctuations in daily death numbers (Bell et al., 2004). The same analytical protocol has been used in the Public Health and Air Pollution in Asia (PAPA) project to investigate the short-term effects of air pollution on daily mortality in four Asian cities (Kan et al., 2008; Wong et al., 2008).

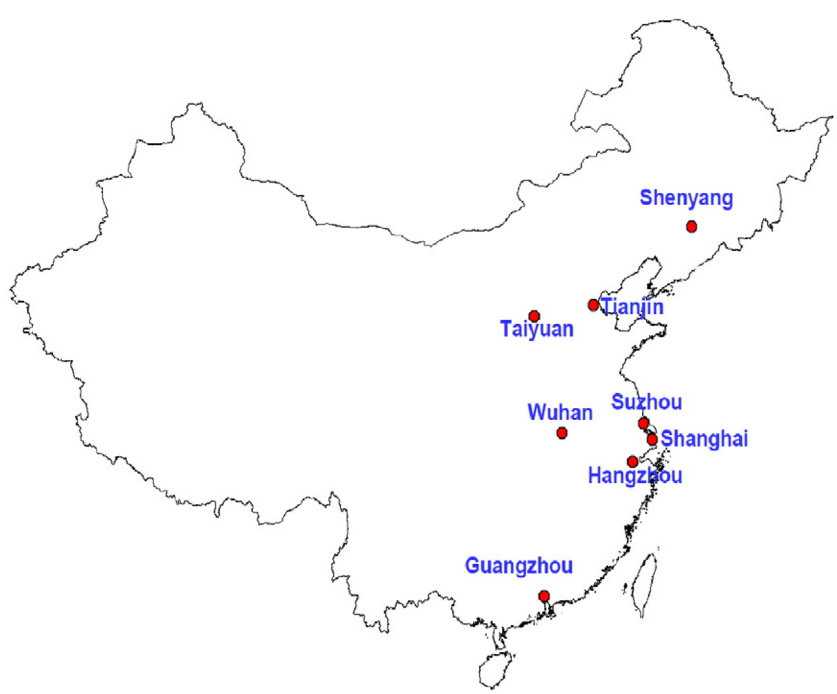

Fig. 1. Location of eight Chinese cities.

Table 1
Descriptive data on the population, study period, and number of daily deaths in eight Chinese Cities.

City	Population (million)	Study Period	Mean number of deaths per day		
			Total	Cardiovascular	Respiratory
Guangzhou	6.5	2007–2008	80	30	15
Hangzhou	2.5	2002–2004	20	7	4
Shanghai	8.5	2001–2008	117	45	13
Shenyang	6.4	2005–2008	67	32	7
Suzhou	4.1	2005–2008	34	13	5
Taiyuan	2.6	2004–2008	24	9	2
Tianjin	1.2	2005–2008	11	7	1
Wuhan	4.5	2003–2005	58	33	7

We first built the basic models for daily mortality not including the PM_{10} and weather variables. We incorporated smoothed spline functions of time, which can accommodate nonlinear and non-monotonic patterns between mortality and time, offering a flexible modeling tool. Partial autocorrelation function (PACF) was used to guide the selection of *df* (Kan et al., 2008; Wong et al., 2008). Specifically, 4–6 *df* per year was used for time trend (Kan et al., 2008; Wong et al., 2008). When the absolute magnitude of the PACF plot was less than 0.1 for the first two lag days, the core models were regarded as adequate (Pope and Dockery, 2006). If this criterion was not met, auto-regression terms were used to reduce autocorrelation (Kan et al., 2008). Day of the week (DOW) was included as dummy variable in the basic models. After we established the basic models, we introduced the PM_{10} and weather variables (mean temperature and relative humidity) and analyzed their effects on daily mortality. Based on the previous literature (Dominici et al., 2005, 2006; Kan et al., 2008; Wong et al., 2008), we used 3 *df* (whole period of study) for weather conditions to control for their effects on mortality. Residuals of the core models were examined to check whether there were discernable patterns and autocorrelation by means of residual plots and PACF plots.

Single-day lag models were reported to underestimate the cumulative effect of air pollution on mortality (Bell et al., 2004); therefore, we used 2-day moving average of current and previous day concentrations of PM_{10} (lag01) (Kan et al., 2008). We used current-day (lag0) temperature.

We used two approaches to explore the possible effect modification by extreme temperature. Firstly, we fitted non-parametric response surface models to identify the joint effects of PM_{10} and temperature on daily mortality, which can graphically illustrate the potential interacting effect. We used a GAM with thin-plate spline to fit a response surface to capture the relation between the two main independent variables and the dependent variable without assuming linearity (Li et al., 2011; Stafoggia et al., 2008). Secondly, we stratified the effects of PM_{10} by temperature. Compared with other methods to detect the effect modification, temperature stratification used fewer parameters and gives a simple and quantitative comparison of the estimate effects of pollutants in the various temperature stratum (Roberts, 2004). Consistent with a prior study (Roberts, 2004), we set the upper (U) and lower (L) temperature cut-points equal to the 95th and 5th percentiles of temperature. Due to the inherently arbitrary or subjective choice of cut-point values, a sensitivity analysis was performed to address the sensitivity of the estimated effects of air pollutants to the choice of cut-point values (97th and 3rd; 93rd and 7th; 90th and 10th). We tested the statistical significance of differences between effect estimates of the temperature strata (e.g. the PM_{10}'s effect between "normal" temperature and lower temperature days) by calculating the 95% confidence interval (95% CI) as $\left(\hat{Q}_1-\hat{Q}_2\right)\pm 1.96\sqrt{\left(S\hat{E}_1\right)^2+\left(S\hat{E}_2\right)^2}$, where $\hat{Q}_1$ and $\hat{Q}_2$ are the estimates for the two categories, and $S\hat{E}_1$ and $S\hat{E}_2$ are their respective standard errors (Chen et al., 2012; Zeka et al., 2006). Using a fixed- or random-effects model, we combined the estimates of eight cities to obtain the national average estimates of the association of PM_{10} with mortality in different temperature strata. Considering that the extent of effect modification may vary by cities, we examined the stratified effects of PM_{10} in northern and southern Chinese cities, separately.

All analyses were conducted in R 2.10.1 using the MGCV package. The results are presented as the percent change in daily mortality per 10 μg/m^3 increase of PM_{10} concentrations.

3. Results

Table 1 summarizes the population and daily mortality data in the eight Chinese cities. The daily mean numbers of total, cardiovascular and respiratory deaths varied according to the size of the city and ranged from 11 to 119, from 7 to 44, and from 1 to 15, respectively. Cardiorespiratory diseases accounted for approximately half of total non-accidental deaths in these cities.

The average daily concentrations of PM_{10} in the eight Chinese cities ranged from 73.8 μg/m^3 to 131.9 μg/m^3, which were much higher than those reported in developed countries. Generally, PM_{10} levels in northern Chinese cities were higher than those in southern Chinese cities. The average temperature ranged from 8.2 °C to 22.8 °C. The mean temperature levels in northern Chinese cities were lower than in southern Chinese cities (Table 2).

Fig. 2 shows the potential interacting effect of PM_{10} and temperature on total non-accidental mortality in each city, using joint response

Table 2
Summary statistics of daily PM_{10} concentrations and mean temperature in eight Chinese cities.

	City	Minimum	P(5)	P(25)	P(50)	P(75)	P(95)	Maximum
PM_{10} (μg/m^3)	Guangzhou	11.0	24.7	44.0	65.0	91.0	161.3	236.0
	Hangzhou	14.0	47.0	80.0	113.0	145.0	232.0	476.0
	Shanghai	14.0	36.5	56.3	84.0	128.7	225.8	566.8
	Shenyang	20.9	52.6	82.8	106.8	134.4	215.1	474.0
	Suzhou	10.0	32.0	56.0	80.0	113.0	184.6	428.0
	Taiyuan	15.0	45.8	90.4	123.7	158.7	251.2	481.0
	Tianjin	10.0	36.0	63.0	87.0	124.0	213.2	480.0
	Wuhan	25.0	54.0	88.0	124.0	165.8	235.1	370.0
Temperature (°C)	Guangzhou	5.4	11.7	18.3	24	27.8	31.2	33.5
	Hangzhou	−1.4	4.2	10.9	18.5	25.0	30.7	36.4
	Shanghai	−2.4	4.0	10.3	18.3	24.7	30.7	34.0
	Shenyang	−22.0	−14.0	−3.0	10.0	20.0	25.0	28.0
	Suzhou	−2.80	2.0	9.2	18.3	25.0	30.2	33.8
	Taiyuan	−13.6	−6.1	1.6	12.4	20.9	26.1	30.5
	Tianjin	−10.5	−4.3	2.7	14.4	23.8	28.3	31.3
	Wuhan	−1.5	2.7	9.6	19.0	25.7	31.9	35.8

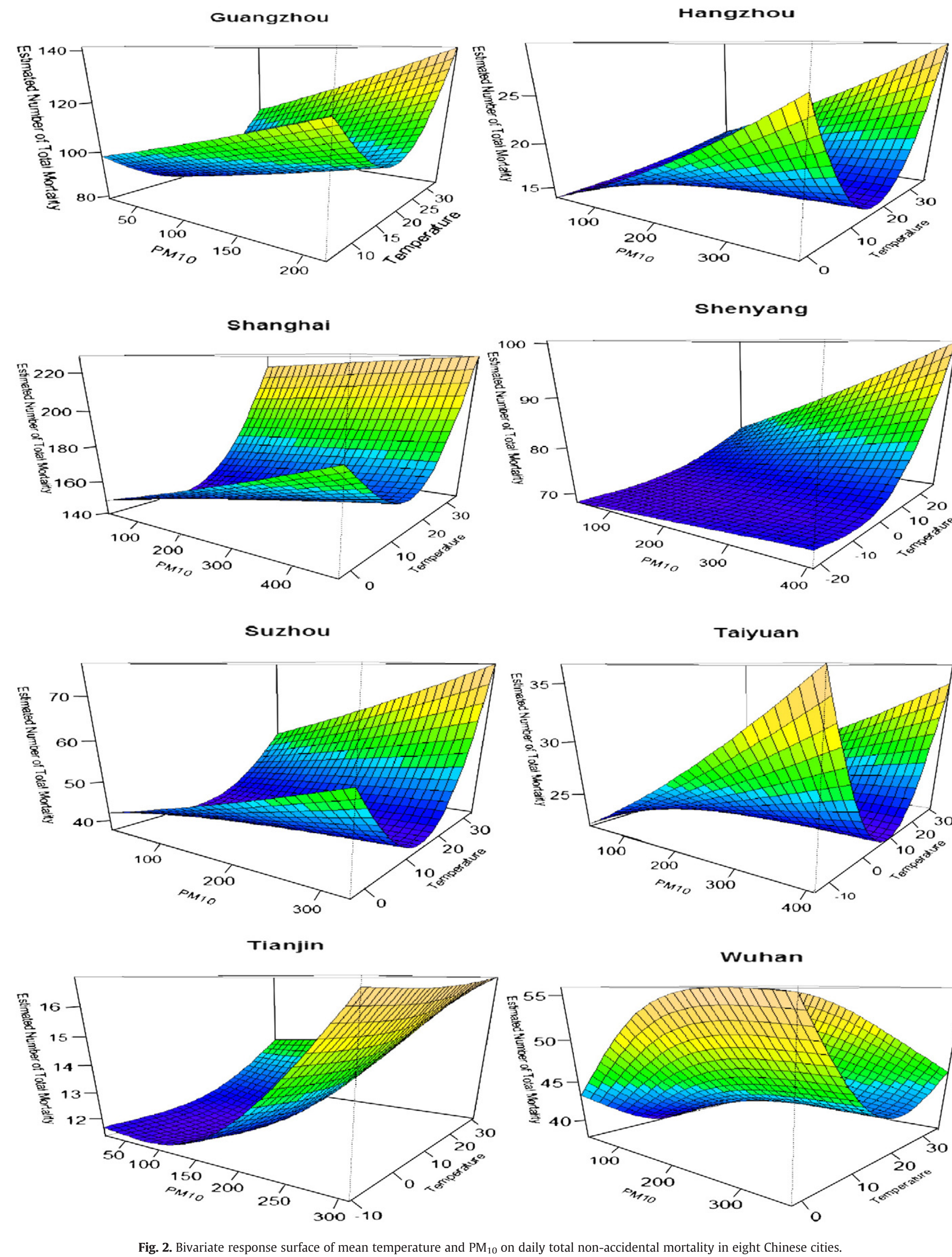

Fig. 2. Bivariate response surface of mean temperature and PM_{10} on daily total non-accidental mortality in eight Chinese cities.

surfaces. When both PM_{10} and temperature were at high levels, the death risks peaked. A visual inspection suggested that the interaction of PM_{10} with low temperature was less significant compared with high temperature.

Table 3 provides city-specific and national average associations of PM_{10} with daily mortality, stratified by temperature (<5%, 5–95%, and >95%). Generally, we found that extreme temperature (>95%) elevated mortality risk of PM_{10} remarkably. Among various temperature strata, for example, the associations of PM_{10} with total mortality were the strongest in extreme high temperature days, except in Guangzhou and Hangzhou where the strongest association appeared in the extreme cold days.

On "normal" temperature (5th to 95th percentile) days, the combined analysis showed that a 10 μg/m^3 increment in PM_{10} corresponded to 0.54% (95% CI, 0.39 to 0.69) increase of total mortality, 0.56% (95% CI, 0.36 to 0.76) increase of cardiovascular mortality, and 0.80% (95% CI, 0.64 to 0.96) increase of respiratory mortality (Table 3). On high-temperature (>95th percentile) days, the combined estimates increased to 1.35% (95% CI, 0.80 to 1.91) for total mortality (p value for comparison with "normal" temperature days<0.05), 1.57% (95% CI, 0.69 to 2.46) for cardiovascular mortality (p<0.05), and 1.79% (95% CI, 0.75 to 2.83) for respiratory mortality (p>0.05). On low-temperature (<5th percentile) days, the estimates were 0.74% (95% CI, 0.32 to 1.17) (p>0.05), 0.50% (95% CI, 0.12 to 0.88) (p>0.05), and 0.62% (95% CI, −0.28 to 1.53) (p>0.05) for total, cardiovascular and respiratory mortality respectively.

The effect modification by extreme high temperature was statistically significant in southern Chinese cities, but not in northern Chinese cities (Table 4). Sensitivity analysis using alternative cut-points (3rd, 7th and 10th percentile) showed similar trends as the 5th percentile cut-point (see online supplement, Fig. 1).

4. Discussion

Our multi-city analysis in eight Chinese cities showed that extreme high temperature significantly increased the associations of PM_{10} with total and cardiovascular mortality. In contrast with previous studies (Carder et al., 2008), we did not find significant effect modification by extreme low temperature. Since extreme high temperature is related with global warming and particulate air pollution is one of the major public health concerns in China (Kan et al., 2012), our observation that extreme high temperature intensified the health hazards of PM_{10} may have important public health significance in China. To our knowledge, this is the first multi-city study in Asian developing region to explore the effect modification by temperature on air pollution health impacts.

Although the underlying mechanism is still unclear, several explanations have been proposed for the synergistic effects of high temperature and particulate air pollution. Previous studies have shown that extreme high temperature might increase the workload of cardiovascular system and induce the onset of adverse cardiovascular event (Haines and Patz, 2004). In Shanghai, China, for example, heat wave was associated with increased cardiovascular mortality (Huang et al., 2010) and hospital visits (Ma et al., 2011). Changes in high-density lipoprotein (HDL), low-density lipoprotein (LDL) and heart rate variability (HRV) associated with an increase in ambient temperature may be among the underlying mechanisms of temperature-related cardiovascular disorders (Halonen et al., 2011; Ren et al., 2011). Increased counts of red blood cell and blood viscosity may also explain the increased mortality from arterial thrombosis in hot weather (Keatinge et al., 1986). It has also been known that marked changes in ambient temperature can cause physiological stress and alter a person's physiological response to air pollutants, perhaps making them more susceptible to the adverse effects of PM_{10}. Moreover, it should be noted that

Table 3
Percent change in daily mortality and 95% CI per 10 μg/m^3 increment in PM_{10} in eight Chinese cities[a].

	City	Temperature stratum		
		Low (5% L)	Normal (5%–95%)	High (95% H)
Total mortality	Guangzhou	**2.80** (**1.93**, **3.66**)*	1.08 (0.85, 1.31)	**2.50** (**1.87**, **3.12**)*
	Hangzhou	**1.31** (**0.80**, **1.82**)*	0.42 (0.14, 0.69)	0.45 (−0.32, 1.21)
	Shanghai	0.19 (−0.01, 0.39)	0.41 (0.32, 0.50)	**0.87** (**0.61**, **1.12**)*
	Shenyang	−0.01 (−0.31, 0.30)	0.33 (0.16, 0.49)	0.44 (0.19, 0.69)
	Suzhou	0.17 (−0.33, 0.67)	0.43 (0.22, 0.64)	**2.17** (**1.61**, **2.72**)*
	Taiyuan	0.49 (0.11, 0.87)	0.36 (0.18, 0.53)	**0.83** (**0.45**, **1.22**)*
	Tianjin	1.56 (0.75, 2.36)	0.78 (0.47, 1.08)	1.23 (0.42, 2.03)
	Wuhan	0.37 (−0.03, 0.77)	0.62 (0.46, 0.78)	**2.42** (**1.93**, **2.91**)*
	Overall	0.74 (0.32, 1.17)	0.54 (0.39, 0.69)	**1.35** (**0.80**, **1.91**)*
Cardiovascular mortality	Guangzhou	**3.18** (**1.80**, **4.55**)*	1.25 (0.88, 1.62)	**3.09** (**2.05**, **4.14**)*
	Hangzhou	0.26 (−0.64, 1.16)	0.10 (−0.37, 0.57)	0.06 (−1.28, 1.39)
	Shanghai	0.31 (−0.01, 0.63)	0.44 (0.30, 0.58)	**1.23** (**0.81**, **1.65**)*
	Shenyang	0.17 (−0.27, 0.62)	0.39 (0.15, 0.63)	0.15 (−0.23, 0.52)
	Suzhou	0.10 (−0.68, 0.89)	0.39 (0.05, 0.73)	**2.70** (**1.77**, **3.63**)*
	Taiyuan	0.20 (−0.43, 0.83)	0.31 (0.02, 0.60)	0.44 (−0.22, 1.09)
	Tianjin	0.95 (−0.12, 2.02)	0.98 (0.58, 1.37)	1.79 (0.74, 2.85)
	Wuhan	0.61 (0.09, 1.13)	0.69 (0.48, 0.91)	**3.19** (**2.55**, **3.84**)*
	Overall	0.50 (0.12, 0.88)	0.56 (0.36, 0.76)	**1.57** (**0.69**, **2.46**)*
Respiratory mortality	Guangzhou	3.05 (1.11, 5.00)	1.41 (0.89, 1.94)	**3.21** (**1.80**, **4.61**)*
	Hangzhou	1.77 (0.69, 2.85)	0.76 (0.16, 1.37)	1.84 (0.13, 3.54)
	Shanghai	−0.40 (−0.95, 0.14)	0.69 (0.46, 0.93)	0.37 (−0.42, 1.16)
	Shenyang	0.84 (−0.11, 1.78)	0.78 (0.27, 1.30)	1.09 (0.29, 1.89)
	Suzhou	−1.04 (−2.38, 0.03)	0.55 (−0.02, 1.11)	1.23 (−0.37, 2.82)
	Taiyuan	1.45 (0.22, 2.68)	0.95 (0.34, 1.55)	0.34 (−1.21, 1.89)
	Tianjin	1.59 (−1.41, 4.60)	0.57 (−0.70, 1.85)	2.53 (−0.67, 5.74)
	Wuhan	−0.91 (−1.96, 0.14)	0.85 (0.0.41, 1.29)	**4.35** (**3.02**, **5.69**)*
	Overall	0.62 (−0.28, 1.53)	0.80 (0.64, 0.96)[b]	1.79 (0.75, 2.83)

[a] "Low" means the day that daily mean temperature is below the 5th percentile of data; "Normal" means the day that daily mean temperature is above the 5th percentile and below the 95th percentile of data; "High" means the day that daily mean temperature is above the 95th percentile of data.
[b] Fix-effect model was used.
* The difference was significant (p<0.05) when comparing with the normal temperature days.

Table 4
Percent (%) increase in daily mortality associated with 10 μg/m^3 increase in PM_{10} in northern and southern Chinese cities.

	Area[a]	Temperature stratum[b]		
		Low (5% L)	Normal (5%–95%)	High (95% H)
Total mortality	Northern cities	0.58 (−0.11, 1.27)	0.45 (0.23, 0.67)	0.72 (0.31, 1.12)
	Southern cities	0.87 (0.23, 1.52)	0.59 (0.37, 0.81)	**1.69** (**0.85**, **2.53**)*
Cardiovascular mortality	Northern cities	0.26 (−0.08, 0.60)[c]	0.53 (0.18, 0.88)	0.65 (−0.12, 1.42)
	Southern cities	0.67 (0.06, 1.28)	0.58 (0.30, 0.87)	**2.10** (**1.00**, **3.19**)*
Respiratory mortality	Northern cities	1.10 (0.37, 1.82)[c]	0.83 (0.45, 1.20)[c]	1.01 (0.32, 1.70)[c]
	Southern cities	0.35 (−0.88,1.59)	0.79 (0.61,0.97)[c]	2.18 (0.56,3.80)

[a] Northern Chinese cities included Shenyang, Tianjin, and Taiyuan; southern Chinese cities included Suzhou, Shanghai, Wuhan, Hangzhou, Guangzhou.
[b] "Low" means the day that daily mean temperature is below the 5th percentile of data; "Normal" means the day that daily mean temperature is above the 5th percentile and below the 95th percentile of data; "High" means the day that daily mean temperature is above the 95th percentile of data.
[c] Fix-effect model was used.
* The difference was significant ($p<0.05$) when comparing with the normal temperature days.

most PM_{10}-related deaths occur in elderly persons (Kan et al., 2008), whose ability to thermo-regulate body temperatures is reduced (Kenney and Hodgson, 1987) and sweating thresholds are generally elevated in comparison with younger persons (Foster et al., 1976). Therefore, interacting effect between PM_{10} and extreme high temperature is biologically plausible.

We observed significant effect modification by extreme high temperature in southern Chinese cities only (Table 4). In southern cities, the 95th percentile of daily mean temperature was much higher than in northern cities; thus, the exposure intensity of high temperature was possibly stronger in south China.

Our findings in eight Chinese cities are consistent with earlier single-city analyses in China (Li et al., 2011; Qian et al., 2008) and other parts of the world. Both studies in Tianjin (Li et al., 2011) and Wuhan (Qian et al., 2008) observed statistically significant interactions between PM_{10} and temperature on total and cardiorespiratory mortality and found high temperature substantially strengthened the effects of PM_{10} on daily mortality. In Brisbane, Australia, Ren et al. found temperature could modify the effects PM_{10} on cardiorespiratory hospital admissions and emergency visits, total non-accidental mortality and cardiovascular mortality (Ren and Tong, 2006; Ren et al., 2006). In nine Italian cities, Stafoggia et al. found much higher PM_{10} effects on mortality during warmer days (Stafoggia et al., 2008). In Cook and Allegheny Counties in the US, evidence that the effect of particulate air pollution on mortality may depend on temperature found (Roberts, 2004). A study in Seoul city of Korea also observed a considerable increase in the association between mortality and air pollution in the summer season with high temperatures and old people were especially vulnerable to air pollution at extremely high temperature (Park et al., 2011). However, several other studies reported negative finding of the interaction between temperature and air pollution. A study in Christchurch, New Zealand reported that high temperatures and particulate air pollution were independently associated with increased daily mortality (Hales et al., 2000), which was consistent with Samet's study (Samet et al., 1998). Heterogeneity of the interaction between temperature and PM_{10} in various cities may reflect the characteristics of the study sites, such as prevalence of air-conditioning or heating systems, weather patterns, sensitivity of local residents to air pollution (e.g. SES, age, and smoking rate), air pollution levels, and components of pollution mixture.

A number of studies have investigated the interaction between air pollution and season (Peng et al., 2005; Wagner, 2004). This study did not investigate the seasonal issue; instead, we focused on extreme temperatures, since temperature and season are related. Our finding of effect modification by extreme high temperature is consistent with prior seasonal analyses in the US (Bell et al., 2005) and Europe (Bremner et al., 1999) reporting greater effects of air pollution in the warm or hot season. In London, for example, the effects for air pollution were observed to be stronger in the warm season than in the cool season (Bremner et al., 1999). The combined analysis of data from nine European cities also showed that air pollution had slightly stronger effect during the warm season than during the cool season (Zmirou et al., 1998).

Our analysis has strengths and limitations. These eight Chinese cities offer advantages for the study of the temperature-PM_{10} interaction in that they are generally very densely populated. As in most previous time-series studies, measurement error could not be eliminated when we simply averaged the measurements across various monitoring stations as the proxy for population exposure to air pollution and temperature. Because we were unable to measure the "true" population exposures in these seventeen cities, we could not determine the direction of the bias and its impact on our conclusions. Also, the magnitude and directions of the impact produced by measurement are very complicated to quantify, especially in the interaction models. Finally, housing characteristics (e.g. air conditioning use) may modify the effect modification by temperature; however, these informations were not available in most Chinese cities we examined.

In conclusion, our study showed that extreme high temperature increased the associations of PM_{10} with daily mortality in eight Chinese cities. These findings may have implication for the health impact associated with both air pollution and global climate change.

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