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Particulate matter modifies the magnitude and time course of the non-linear temperature-mortality association

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ABSTRACT

It remains uncertain whether air pollution modifies the magnitude and time course of the temperature-mortality association. We applied a distributed lag non-linear model (DLNM) combined with non-linear interaction terms to assess the modifying effects of particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}) on the association between mean temperature and mortality in Guangzhou, China. We found that both cold and hot effects increased with the quartiles of PM_{10}. The elderly were more vulnerable to cold and hot effects. Men suffered more from cold-related mortality than women, with the gender difference enlarging with the quartiles of PM_{10}. We identified statistically significant interaction effects between PM_{10} and mean temperature on mortality (except for respiratory mortality). Cold and hot effects basically appeared acutely on highly polluted days, while effects were delayed on lowly polluted days. The findings indicate the importance of reducing PM_{10} emission on extremely temperature days.

1. Introduction

Both ambient air pollution and extreme temperatures are risk hazards for human health worldwide (Barnett, 2007; Kan et al., 2008; Qian et al., 2008; Romieu et al., 2012; Tong et al., 2012; Yang et al., 2012). It is widely accepted that effects of air pollution and temperature on mortality may confound each other (Qian et al., 2008; Romieu et al., 2012; Wu et al., 2013; Yang et al., 2012). In addition, one factor's influences on health outcomes may differ by the level of the other one. However, there has been limited assessment of their modifying effects. A few studies have reported the modifying effects of temperature on the association between air pollution and mortality (Carder et al., 2008; Li et al., 2011; Lin and Liao, 2009; Meng et al., 2012; Qian et al., 2008; Ren et al., 2009; Stafoggia et al., 2008). Only two studies evaluated the effect modification of air pollution on temperature-mortality association, and their analytical models were built based on an assumption that interaction effects between air pollution and temperature are linear (Breitner et al., 2014; Ren et al., 2006). There is ample evidence of non-linear effects of temperature on mortality; therefore we speculate that the interaction effects between air pollution and temperature are non-linear.

A growing body of research indicates that effects of hot temperatures on mortality might be usually acute, while effects of cold temperatures appear late and can persist for weeks, much longer than those of hot temperatures (Anderson and Bell, 2009; Guo et al., 2011; Yang et al., 2012). Even though this discrepancy has been considered in the majority of recent studies concerned with temperature-mortality association, most previous studies investigating interaction effects between air pollution and temperature examined the effects of temperature for a single lag (Meng et al., 2012; Ren et al., 2006), or chose a priori lag period to appraise cumulative effects (Carder et al., 2008; Roberts, 2004). These approaches of choosing lag are arbitrary and not exact to assess lagged effects of temperature (Guo et al., 2011). Furthermore, there has not been examined previously whether the time courses of temperature effects differ by air pollution level.

Health impacts of climate change are likely to be more serious in developing countries (IPCC, 2014). In the Asian region where burdens of disease attributable to ambient air pollution have been aggravated (HEI, 2004), PM_{10} is a critical contaminant that has a great detrimental influence on public health (Cornie, 2012). In recent years, like most of cities in the Asia region, Guangzhou, the transportation, industrial and trade center of Southern China, is

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suffering from air pollution and climate change. This study explored whether PM_{10} modifies the non-linear shape and time course of the temperature-mortality association in Guangzhou, China.

2. Methods

2.1. Data

Guangzhou, a city having a typically subtropical climate, is the largest metropolis in southern China with the latitude of 23°07′ N. In 2011, there were over 12.7 million permanent residents in Guangzhou. We obtained individual data for all registered deaths between 1 January 2003 and 31 December 2011 from Guangzhou Center for Disease Control and Prevention. The causes of death were coded according to the International Classification of Diseases, the tenth version (ICD-10). Non-accidental (ICD-10: A00-R99), cardiovascular (ICD-10: I00-I99) and respiratory (ICD-10: J00-J99) mortality were examined. All-causes deaths were stratified by age (≥ 65 and <65 years) and gender.

Daily meteorological data on mean temperature, relative humidity and atmospheric pressure were obtained from China Meteorological Data Sharing Service System. Weather data were collected from Guangzhou Weather Station, which is the only basic weather station in Guangzhou, as part of the global meteorological information sharing network.

Guangzhou Bureau of Environmental Protection provided daily air pollution data on particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}). In this study, we selected seven fixed-site air monitoring stations as they had valid daily measurements for the entire study period. The average daily concentrations of PM_{10} in the entire territory of Guangzhou were computed using the centering method (Wong et al., 2001). Details for monitoring stations and calculation of concentrations of PM_{10} were described in our previous studies (Ou et al., 2013; Li et al., 2014).

2.2. Statistical analysis

A quasi-Poisson regression model combined with a distributed lag non-linear model (DLNM) was used to examine the effects of mean temperature on mortality categories:

$$
\begin{aligned}
Y_t \sim \text{Poisson}(\mu_t) Log(\mu_t) &= \alpha + ns(Time_t, df_{time}) + \eta DOW_t \\
&\quad + \upsilon Holiday_t + ns(RH_t, 3) + ns(PRE_t, 3) + \beta PM_{10t,l1} \\
&\quad + \gamma Temp_{t,l2} + ns(Temp_t, df_{DLNM}) : PM_{10t} \\
&= \alpha + COVs + \gamma Temp_{t,l2} + ns(Temp_t, df_{DLNM}) : PM_{10t}
\end{aligned}
$$

where t is the calendar day of observation; Y_t is the observed daily death counts on day t; α is the intercept; $ns(\ldots)$ is a natural cubic spline. We used 7 degrees of freedom (df) per year for time ($Time_t$) which can adequately control for long-term trends and seasonal variations of daily mortality (Bhaskaran et al., 2013; Yang et al., 2012). DOW_t are dummy variables indicating the day of week on day t, and η is the vector of coefficients. $Holiday_t$ is an indicator variable that is "1" if day t was a *holiday*, and υ is the coefficient. 3 df was used to smooth mean relative humidity (RH_t) and atmospheric pressure (PRE_t) (Braga et al., 2001; Guo et al., 2011; Muggeo and Hajat, 2009). $PM_{10t,l1}$ and $Temp_{t,l2}$ are matrices obtained by applying the DLNM to PM_{10} and mean temperature, respectively. β and γ are vectors of coefficients for $PM_{10t,l1}$ and $Temp_{t,l2}$. $l1$ and $l2$ are lag days for PM_{10} and mean temperature, respectively. The effects of PM_{10} were controlled for using a linear function for PM_{10} and lag up to 1 day (Alessandrini et al., 2013; Kan et al., 2008; Qian et al., 2008; Wong et al., 2008). We used 20 days as the maximum lag for mean temperature (Guo et al., 2013; Yang et al., 2013). The dfs for mean temperature and lag were selected by the minimum value of Akaike Information Criterion (AIC) for the quasi-Poisson model. In the final model, dfs were specified to be 6 and 5 for mean temperature and its lag, respectively.

To examine the interaction effects between PM_{10} and mean temperature, we added interaction terms of a linear function for PM_{10} and a natural cubic spline for mean temperature of which df was determined in the DLNM (i.e., $df_{DLNM} = 6$). We generated three-dimensional exposure-response surfaces to visualize the joint cumulative effects between PM_{10} and mean temperature on mortality. In addition, we calculated cold effects (i.e., mortality risk comparing the 1st to the 10th percentile of mean temperature) and hot effects (i.e., mortality risk comparing the 99th to the 90th percentile of mean temperature), given that PM_{10} equaled 0 μg/m^3, the 25th (48.6 μg/m^3), 50th (71.4 μg/m^3) and 75th (102.6 μg/m^3) percentile of PM_{10}, respectively. To test the statistical significance of the interaction effects, an F test was employed to compare models with and without interaction terms (R Core Team, 2014a).

To determine whether the time courses of temperature effects on mortality varied on highly and lowly polluted days, we categorized PM_{10} into two levels (i.e., high and low) using a cutoff value of 50 μg/m^3, the standard of WHO Air Quality Guidelines (Clean Air Asia, 2012), and separated the data into two parts based on PM_{10} levels. Time courses of temperature effects given that PM_{10} equaled the 25th and 75th percentile of PM_{10} were presented.

Sensitivity analyses were performed by changing the df for time to 6–11 per year to determine whether we sufficiently controlled for long-term trends and seasonality using 7 df in the primary analysis, and extending the maximum lag from 20 days to 21–30 days for mean temperature.

Table 1
Summary statistics for daily weather conditions, PM_{10} and number of deaths in Guangzhou, China during 2003–2011.

Variables	Mean ± SD	Minimum	Percentiles			Maximum
			25th	50th	75th	
Mean temperature (°C)	22.7 ± 6.3	5.4	18.3	24.2	27.8	34.2
Mean humidity (%)	71.4 ± 13.0	20.0	64.0	73.0	81.0	99.0
Mean air pressure (hpa)	1008.2 ± 6.9	988.7	1003.0	1007.9	1013.4	1027.2
PM_{10} (μg/m^3)	80.6 ± 44.6	7.0	48.6	71.4	102.6	370.1
Daily number of deaths						
All-causes	65 ± 14	21	56	63	73	248
Non-accidental	63 ± 14	20	53	60	70	233
Cardiovascular diseases	24 ± 7	6	19	23	28	102
Respiratory diseases	12 ± 4	2	9	11	14	46