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Short-term Effects of Ambient Gaseous Pollutants and Particulate Matter on Daily Mortality in Shanghai, China

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Abstract: Short-term Effects of Ambient Gaseous Pollutants and Particulate Matter on Daily Mortality in Shanghai, China: Guohai CHEN, *et al.* Shanghai Environmental Monitoring Center, China— Identification of the specific pollutants contributing most to the health hazard of the air pollution mixture may have important implications for environmental and social policies. In the current study, we conducted a time-series analysis to examine the specific effects of major air pollutants [particulate matter less than 10 microns in diameter (PM_{10}), sulfur dioxide (SO_2), and nitrogen dioxides (NO_2)] on daily mortality in Shanghai, China, using both single-pollutant and multiple-pollutant models. In the single-pollutant models, PM_{10}, SO_2, and NO_2 were found to be associated with mortality from both all non-accidental causes and from cardiopulmonary diseases. Unlike some prior studies in North America, we found a significant effect of gaseous pollutants (SO_2 and NO_2) on daily mortality even after adjustment for PM_{10} in the multiple-pollutant models. Our findings, combined with previous Chinese studies showing a consistent, significant effect of gaseous pollutants on mortality, suggest that the role of outdoor exposure to SO_2 and NO_2 should be investigated further in China.
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Key words: Outdoor air pollution, Gaseous pollutants, Particle, Time-series

Short term exposure to outdoor air pollution has been linked to adverse health effects, including increased mortality, increased rates of hospital admissions and emergency department visits, exacerbation of chronic respiratory conditions (*e.g.*, asthma), and decreased lung function[1]. Recent multi-city analyses conducted in the U.S., Canada and Europe provide further evidence supporting the coherence and plausibility of these associations[2–6]. Most of these studies were conducted in developed countries, and only a small number of studies have been conducted in Asia[7]. The need remains for studies of cities in developing countries, where characteristics of outdoor air pollution (*e.g.* air pollution level, chemical composition and size of particles, and fate and transport of pollutants), meteorological conditions and socio-demographic patterns may differ from North America and Western Europe.

Ambient air pollution is a complex mixture composed of both solid particles and gaseous pollutants. Although the strongest evidence linking outdoor air pollutants with adverse health effects is for solid particulates (*e.g.* PM_{10}), many researchers have reported associations for gaseous pollutants[5, 8]. In China, for example, one study conducted by Xu et al. showed that it was SO_2, not total suspended particle (TSP), that was associated with mortality increase in Beijing[9]. Similar results have also been presented by the studies conducted worldwide, which have led some authors to conclude that the pollutants measured and included in models of daily mortality might be better interpreted as indicators of the biologically relevant pollutant mixture and that the best indicators might vary in different geographic areas[10]. Obviously, identification of the specific pollutants contributing most to the health hazard of the air pollution mixture may have important implications for environmental and social policies, and for local government in taking steps to protect the total population in general, and the sensitive population in particular.

In the current study, we conducted a time-series analysis to examine the effects of major air pollutants [particulate matter less than 10 microns in diameter

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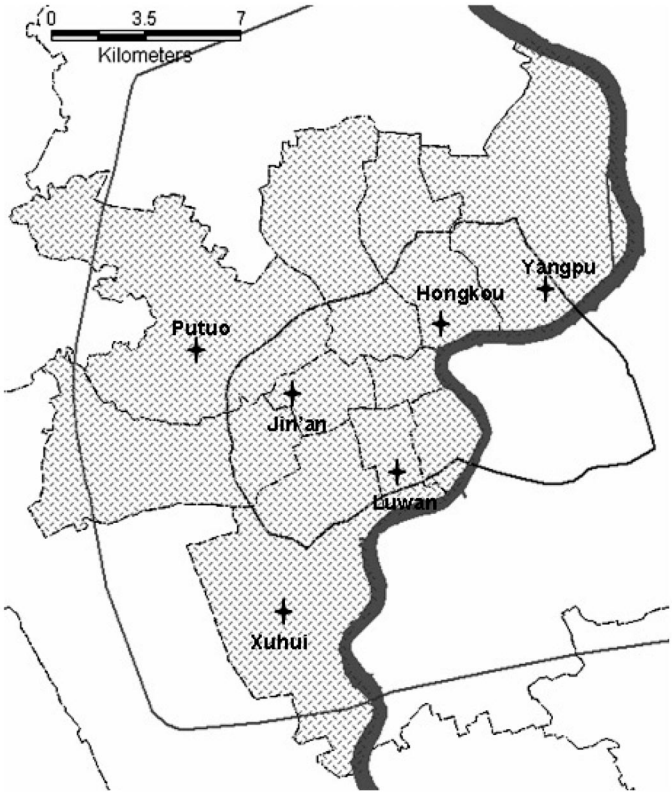

Fig. 1. Map of research area and location of six monitoring stations in Metropolitan Shanghai.

(PM_{10}), sulfur dioxide (SO_2), and nitrogen dioxides (NO_2)] on daily mortality in Shanghai, China, using both single-pollutant and multiple-pollutant models. PM_{10}, SO_2 and NO_2 are criteria pollutants in China and have been regularly monitored since 1996.

Methods

Shanghai, the most populous city in China, is located at the tip of the Yangtze River Delta in eastern China. The city comprises urban/suburban districts and counties, with a total area of 6,341 square kilometres (km^2), and had a population of 13.1 million at the end of 2004, representing about 1% of China's total. Our study area was limited to the traditional nine urban Districts of Shanghai (289 km^2)—Huangpu, Jinan, Luwan, Xuhui, Yangpu, Changnin, Yangpu, Putuo and Zhabei. The target population included all permanent residents living in the area, around 6.3 million in 2004.

Daily mortality data (excluding accidents & injuries) of residents living in the nine urban districts of Shanghai from Jan. 1, 2001 to Dec. 31, 2004 were collected from the database of Shanghai Municipal Center of Disease Control and Prevention (SMCDCP). The death report system in Shanghai was implemented in 1951, and has been computerized since 1990. For both at-home and hospital deaths, physicians complete death certificate cards. The information on the cards is then sent to SMCDCP through a computer network. The database for 2001 and 2002–2004 was coded according to the International Classification of Diseases, Revision 9 (ICD-9) and 10 (ICD 10), respectively. The mortality data were classified into deaths due to all non-accidental causes (ICD-9 <800; ICD-10 A00-R99), cardiovascular diseases (ICD-9 390-459; ICD-10 I00-I99), and respiratory diseases (ICD-9 460-519; ICD-10 J00-J98).

Daily data on levels of PM_{10}, SO_2 and NO_2 from Jan. 1, 2001 to Dec. 31, 2004 in Metropolitan Shanghai were retrieved from the database of the Shanghai Environmental Monitoring Center (SEMC). The daily concentrations for each pollutant were averaged from the available monitoring results of six fixed-site stations located in urban areas of Shanghai and covered by China National Quality Control (Fig. 1). The stations are mandated not to be in direct proximity to traffic, industrial sources, buildings or residential sources of emissions from the burning of coal, waste, or oil. Thus, our monitoring results reflect the background air pollution levels in Shanghai.

Table 1. Summary statistics of daily death numbers, air pollutant concentrations and weather conditions in Shanghai (2001–2004)

	Mean ± SD	Min	25th percentile	Median	75th percentile	Max
Daily death counts						
Total (non-accident)	119.0 ± 22.5	51.0	103.0	115.0	133.0	198.0
Cardiovascular	44.2 ± 11.0	11.0	36.0	43.0	51.0	85.0
Respiratory	14.3 ± 6.4	3.0	10.0	13.0	17.0	45.0
Air pollutants concentrations						
PM_{10} ($\mu g/m^3$)	102.0 ± 64.8	14.0	56.3	84.0	128.3	566.8
SO_2 ($\mu g/m^3$)	44.7 ± 24.2	8.4	27.5	40.0	56.2	183.3
NO_2 ($\mu g/m^3$)	66.6 ± 24.9	13.6	50.2	62.5	79.2	253.7
Meterologic measures						
Mean Temperature (°C)	17.7 ± 8.5	–2.4	10.3	18.3	24.7	34.0
Relative humidity (%)	72.9 ± 11.4	33.3	65.5	73.5	81.0	97.0

To allow adjustment for the effect of weather conditions on mortality, meteorological data (daily minimum, maximum and mean temperature, relative humidity, and dew point temperature) from Jan. 1, 2001 to Dec. 31, 2004 were obtained from the database of the Shanghai Meteorological Bureau (SMB).

All daily mortality, pollutant and meteorological data were validated by an independent auditing team assigned by the Health Effects Institute (HEI), the funding agency of this study.

Statistical analysis

The daily death, air pollution and weather data are linked by date and therefore can be analyzed with a time-series design[11]. Because counts of daily mortality data typically follow a Poisson distribution and the relations between mortality and explanatory variables are mostly non-linear[11], the core analysis was a generalized additive model (GAM) with log link and a Poisson error that accounted for smooth fluctuations in daily mortality.

We first built basic models for various mortality outcomes not including the air pollution and weather variables. We incorporated smoothed spline functions of time, which can accommodate non-linear and non-monotonic patterns between mortality and time, offering a flexible modeling tool[12]. Day of the week (DOW) was also included in the basic models. In our analysis, a partial autocorrelation function (PACF) was used to guide the selection of degrees of freedom (df)[13]. Specifically, we used 4–6 df per year for time trend. When the absolute magnitude of the PACF plot was less than 0.1 for the first two lag days, the basic model was regarded as adequate; if this criteria was not met, auto-regression (AR) terms for lag up to 7 days was introduced to improve the model. In this way, 4, 4 and 5 df per year for time trend, as well as 3, 2 and 4 lag-day AR terms, were used in our basic models for total, cardiovascular and respiratory mortality, respectively.

After we established the basic models, we introduced the pollutant and weather variables and analyzed their effects on mortality outcomes. Based on the previous literature[6, 14, 15], 3 df (whole period of study) for temperature and relative humidity could control well for their effects on mortality and was used in the model.

Briefly, we fitted the following log-linear GAM to obtain the estimated pollution log-relative rate β in Shanghai:

$$\log E(Y_t) = \beta Z_t + DOW + ns(time,df) + ns(temperature,3) + ns(humidity,3) + intercept$$

Here $E(Y_t)$ represents the expected number of deaths on day t; β represents the log-relative rate of mortality associated with a unit increase of air pollutants; Z_t indicates the pollutant concentrations on day t; DOW is day of the week effect; ns(time,df) is the natural spline function of calendar time; and ns(temperature / humidity,3) is the natural spline function of temperature / humidity with 3 df.

We fitted both single-pollutant models and models with a different combination of pollutants (up to two pollutants per model) to assess the individual effect of each pollutant as well as the stability of the pollutants' effects.

All analyses were conducted in R 2.5.1 using the MGCV package[16].

Results

From 2001 to 2004, a total of 173,911 deaths (91,314 males and 82,597 females) were registered in the study population (Table 1). The percentages of total deaths by age group were 0.3% for 0–4, 3.2% for 5–44, 13.0% for 45–64 and 83.5% for 65+, respectively. On average, there were 119.0 non-accidental deaths per day, including 44.2 from cardiovascular diseases and 14.3 from respiratory

Table 2. Correlation coefficients between daily air pollutant concentrations and weather conditions in Metropolitan Shanghai (2001–2004)

	SO_2	NO_2	Temperature	Relative humidity
PM_{10}	0.64	0.71	–0.21	–0.37
SO_2	1.00	0.73	–0.21	–0.52
NO_2		1.00	–0.38	–0.27
Temperature			1.00	0.21

Table 3. Percent increase of mortality outcomes associated with a 10 $\mu g/m^3$ increase of air pollutant concentrations under single and multiple pollutant models*

	Model	Total mortality	Cardiovascular mortality	Respiratory mortality
$PM1_0$	single-pollutant	0.26 (0.14, 0.37)	0.27 (0.10, 0.44)	0.27 (–0.01, 0.56)
	adjusted for SO_2	0.08 (–0.07, 0.22)	0.12 (–0.10, 0.34)	–0.04 (–0.41, 0.33)
	adjusted for NO_2	0.01 (–0.14, 0.17)	0.01 (–0.22, 0.25)	–0.05 (–0.45, 0.34)
	adjusted for SO_2 and NO_2	0.00 (–0.16, 0.16)	0.01 (–0.23, 0.25)	–0.10 (–0.50, 0.30)
SO_2	single-pollutant	0.95 (0.62, 1.28)	0.91 (0.42, 1.41)	1.37 (0.51, 2.23)
	adjusted for PM_{10}	0.80 (0.37, 1.24)	0.69 (0.04, 1.34)	1.45 (0.32, 2.59)
	adjusted for NO_2	0.31 (–0.27, 0.89)	0.05 (–0.83, 0.93)	0.95 (–0.59, 2.50)
	adjusted for PM_{10} and NO_2	0.31 (–0.28, 0.89)	0.04 (–0.85, 0.93)	1.00 (–0.55, 2.56)
NO_2	single-pollutant	0.97 (0.66, 1.27)	1.01 (0.55, 1.47)	1.22 (0.42, 2.01)
	adjusted for PM_{10}	0.94 (0.50, 1.38)	0.98 (0.33, 1.64)	1.32 (0.21, 2.45)
	adjusted for SO_2	0.73 (0.19, 1.27)	0.97 (0.16, 1.80)	0.47 (–0.94, 1.91)
	adjusted for PM_{10} and SO_2	0.73 (0.14, 1.32)	0.95 (0.06, 1.84)	0.62 (–0.92, 2.16)

*Current day temperature and relative humidity (lag 0), and two-day moving average of air pollutants concentrations (lag 01) were used in all the regression models of Table 3.

diseases. Cardiopulmonary disease accounted for 49.1% of the total non-accidental deaths for the urban residents of Shanghai.

During our study period, the mean daily average concentrations of PM_{10}, SO_2 and NO_2 were 102.0 $\mu g/m^3$, 44.7 $\mu g/m^3$ and 66.6 $\mu g/m^3$, respectively. Meanwhile, the mean daily average temperature and relative humidity were 17.7°C and 72.9%, reflecting the subtropical climate in Shanghai.

Generally, PM_{10}, SO_2 and NO_2 had relatively high correlation coefficients with each other, and $PM_{10}/SO_2/NO_2$ concentrations were negatively correlated with mean temperature and relative humidity (Table 2).

Table 3 shows the comparison results of the single-pollutant models and multiple-pollutant models. In the single-pollutant models, significant association was established between levels of air pollutants (PM_{10}, SO_2, and NO_2) and daily total non-accidental mortality as well as cardiorespiratory mortality. An increase of 10 $\mu g/m^3$ of PM_{10}, SO_2 or NO_2 corresponds to 0.25% (95%CI 0.14–0.37%), 0.95% (95%CI 0.62–1.27%) or 0.96% (95%CI 0.66–1.26%) increases of all-cause mortality, respectively.

Figure 2 graphically shows the exposure-response relationship for each pollutant with total mortality in the single-pollutant models. For most concentration levels (>70 $\mu g/m^3$) of PM_{10}, we observed a positive non-linear relationship between PM_{10} and three mortality outcomes. There was an almost linear relationship between SO_2 and total mortality. We did not observe any obvious threshold concentration below which SO_2 had no effect on total mortality. There was a positive non-linear relationship between NO_2 and mortality outcomes.

In the multiple-pollutant models, the effect of PM_{10} on total and cardiovascular morality decreased and became insignificant after adjustment for SO_2, NO_2 or both. PM_{10} has no significant effect on respiratory mortality either before or after adjustment for co-pollutants. The effect of SO_2 on total, cardiovascular and respiratory mortality remained significant after adding PM_{10} into the models; however, the effect of SO_2 became statistically insignificant for all three mortality outcomes after adjustment for NO_2, or both PM_{10} and NO_2. The effect of NO_2 on total and cardiovascular mortality did not alter much when other pollutants were added. The effect of

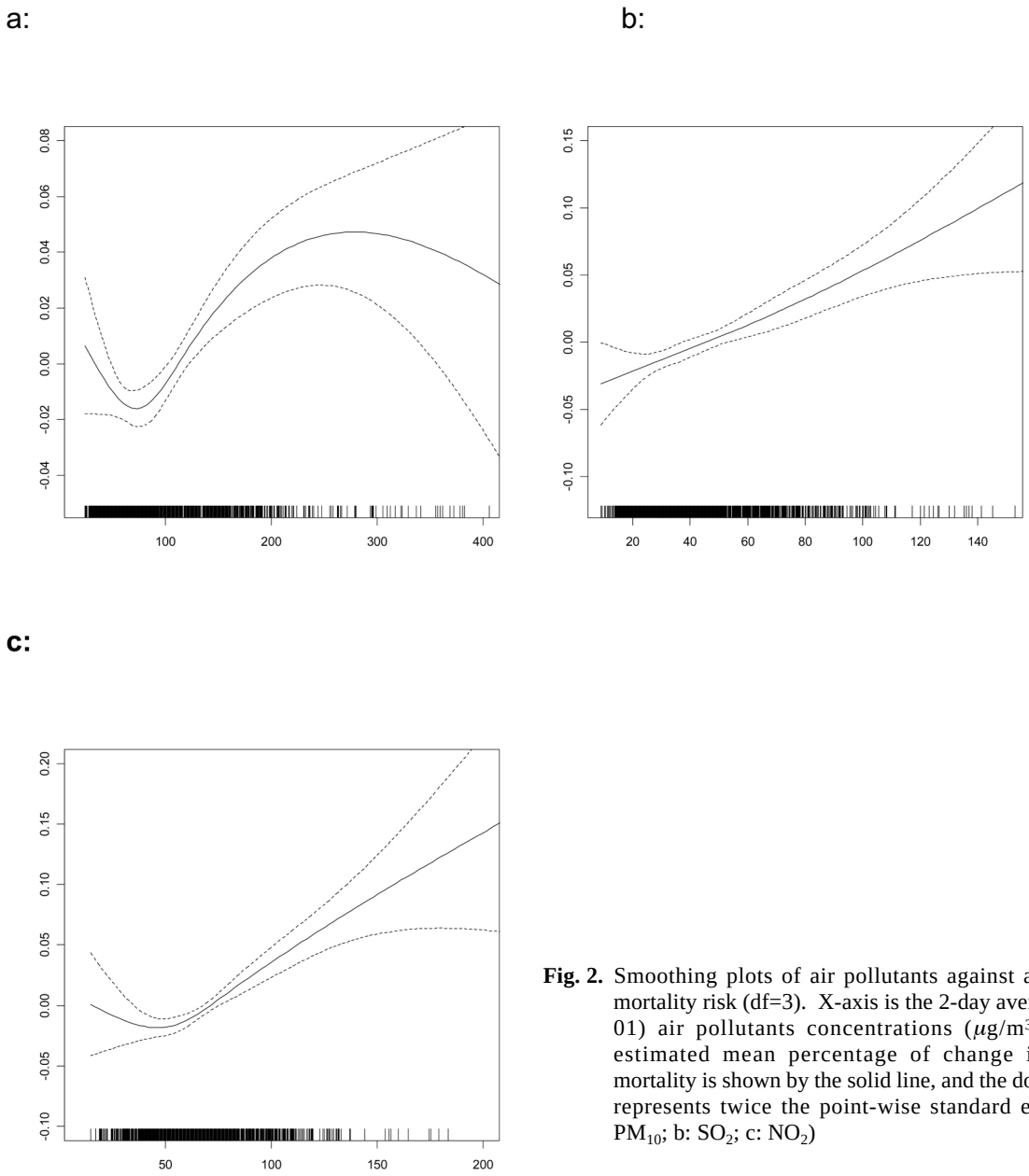

Fig. 2. Smoothing plots of air pollutants against all-cause mortality risk (df=3). X-axis is the 2-day average (lag 01) air pollutants concentrations ($\mu g/m^3$). The estimated mean percentage of change in daily mortality is shown by the solid line, and the dotted line represents twice the point-wise standard error. (a: PM_{10}; b: SO_2; c: NO_2)

NO_2 on respiratory mortality was not affected after adjustment for PM_{10}, but became insignificant after adjustment for SO_2, or both PM_{10} and SO_2.

Discussion

Evidence gained in this time-series analysis shows that outdoor air pollution (PM_{10}, SO_2 and NO_2) was associated with mortality from all causes and from cardiopulmonary diseases in Shanghai in 2001–2004. As in prior studies, we found a significant association between PM_{10} and mortality outcomes in Shanghai, although the size of our estimate was relatively small. We also found a significant effect of gaseous pollutants (SO_2, and NO_2) on daily mortality, even after adjustment for PM_{10}. Although SO_2 and NO_2 contribute to PM formation, the current analysis suggests that they are also pollutants that can independently cause adverse health effects.

SO_2 is a gaseous pollutant produced by fuel combustion, and it can cause bronchoconstriction in normal and asthmatic subjects after short term exposure[17, 18]. SO_2 can be converted to sulphuric acid, which can be carried into the small airways by inhalable particulates and impair lung function in children[19]. Although the high correlation between SO_2 and co-pollutants such as PM_{10} and NO_2 made it difficult to separate its independent effect, an intervention study conducted in Hong Kong provided direct evidence

that SO_2 resulting from sulfur-rich fuels had an effect on cardio-respiratory deaths[20]. Also in Hong Kong, the strongest effects of outdoor air pollution were for gases including SO_2 rather than PM_{10} [21]. Moreover, it is well known that ambient SO_2 is the precursor of SO_4^{2-} or sulfate, an important component of fine particles. Zhang et al. found that the concentration of SO_4^{2-} in the air was closely associated with chronic disease mortality in Beijing, China[22].

Of the pollutants we considered, only NO_2 remained significantly associated with total and cardiovascular mortality after adjustment for co-pollutants. This result is consistent with a recent multi-city analysis in Europe (APHEA-2)[23]. However, in an analysis of 20 U.S. cities within the National Morbidity, Mortality and Air Pollution Study (NMMAPS), no consistent pattern of association between total mortality and NO_2 was found[6]. The difference between NMMAPS and APHEA findings may be attributed to the varying air pollution sources and mixture in the US and Europe[23]. Inhalation of NO_2 may provoke an inflammatory response in the lungs with the consequent release into the circulation of prothrombotic and inflammatory cytokines; a systemic acute phase response of this nature would put people with coronary atheroma at increased risk of plaque rupture and thrombosis. Moreover, exposure to NO_2 may have an adverse effect on cardiac autonomic control, leading to an increased risk of arrhythmia in susceptible patients[24]. For example, acute exposure to NO_2 has been associated with ventricular tachyarrhythmias which are common precursors to sudden cardiac death[25]. Of course, NO_2 could be a marker for other pollutants generated from the same source such as particles. For example, Seaton et al suggested NO_2 is a surrogate for the ultra-fine particle (UFP) number[26]. Therefore, there is a possibility that the effect we observed for NO_2 might be due to other unmeasured pollutant such as UFP.

Of course, given that the present air pollution epidemiologic study used ambient pollutant concentrations as surrogates of personal exposure, the observed health effects attributed to the ambient gaseous pollutants, *e.g.* SO_2 and NO_2, might actually be a result of exposures to fine particles[10, 27, 28]. At present, we cannot conclude that SO_2 and NO_2 are proxies of fine particles or the components of fine particles, and SO_2 and NO_2 may have a direct short-term effect on mortality in Shanghai. However, a consistent, significant effect of SO_2 and NO_2 on mortality observed in China suggests that the role of outdoor exposure to gaseous pollutants should be investigated further.

For air pollution, the shape of the exposure-response relation for mortality has long been of interest as researchers have attempted to supply useful evidence for policymakers seeking to minimize the risk to public health. We did not find a linear exposure-response relationship of total mortality with PM_{10} or NO_2 (Fig. 2), which might have contributed to the relatively lower risk of the two pollutants in our study compared with the findings of prior studies. For PM_{10}, a "U" relationship with mortality risk was found for most concentrations we observed ($\leq$300 $\mu g/m^3$). For NO_2, the mortality risk seems to increase only with higher concentrations above 50 $\mu g/m^3$. Some prior studies have suggested the existence of threshold effects in the population risk level due to air pollution exposure[29]. Given the high correlation between pollutant concentrations (Table 2), the linearity of the relationship between air pollution and mortality should be explored further in the future.

In summary, unlike some prior studies in North America, we found significant effects of SO_2 and NO_2 on mortality outcomes even after adjustment for PM_{10} in Shanghai. Our findings, combined with previous Chinese studies showing a consistent, significant effect of gaseous pollutants on mortality, suggest that the role of outdoor exposure to SO_2 and NO_2 should be investigated further in China.

Shanghai will host the World Expo in 2010, and plans to invest billions of dollars in environment protection to prepare for this momentous event. The results of the current study may supplement useful information on air pollution-related health effects in Shanghai, thereby providing local decision-makers with information needed to set priority of air pollution control measures with the largest health benefits.

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