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Acute effect of ozone exposure on daily mortality in seven cities of Jiangsu Province, China: No clear evidence for threshold

Kai Chen[a,b], Lian Zhou[c], Xiaodong Chen[c], Jun Bi[a,*], Patrick L. Kinney[b,*]

[a] State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing, China
[b] Department of Environmental Health Sciences, Program in Climate and Health, Mailman School of Public Health, Columbia University, New York, NY, USA
[c] Jiangsu Provincial Center for Disease Prevention and Control, Nanjing, China

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ABSTRACT

Background: Few multicity studies have addressed the health effects of ozone in China due to the scarcity of ozone monitoring data. A critical scientific and policy-relevant question is whether a threshold exists in the ozone-mortality relationship.
Methods: Using a generalized additive model and a univariate random-effects meta-analysis, this research evaluated the relationship between short-term ozone exposure and daily total mortality in seven cities of Jiangsu Province, China during 2013–2014. Spline, subset, and threshold models were applied to further evaluate whether a safe threshold level exists.
Results: This study found strong evidence that short-term ozone exposure is significantly associated with premature total mortality. A 10 $\mu g/m^3$ increase in the average of the current and previous days' maximum 8-h average ozone concentration was associated with a 0.55% (95% posterior interval: 0.34%, 0.76%) increase of total mortality. This finding is robust when considering the confounding effect of $PM_{2.5}$, PM_{10}, NO_2, and SO_2. No consistent evidence was found for a threshold in the ozone-mortality concentration-response relationship down to concentrations well below the current Chinese Ambient Air Quality Standard (CAAQS) level 2 standard (160 $\mu g/m^3$).
Conclusions: Our findings suggest that ozone concentrations below the current CAAQS level 2 standard could still induce increased mortality risks in Jiangsu Province, China. Continuous air pollution control measures could yield important health benefits in Jiangsu Province, China, even in cities that meet the current CAAQS level 2 standard.

1. Introduction

Short-term exposure to ambient ozone has been found to be associated with numerous adverse health effects, including increased mortality, increased rates of respiratory hospital admissions and emergency room visits, and decreased lung function (Gryparis et al., 2004; Kinney et al., 1989; Lippmann, 1993; Schwartz, 1996). Recent multicity analyses pooling estimates from city-specific results provide further evidence supporting the causal relationship between short-term ozone exposure and total mortality (U.S. EPA, 2013). However, most of these studies were conducted in North America (Bell and Dominici, 2008; Smith et al., 2009), Latin America (Romieu et al., 2012), and Europe (Katsouyanni et al., 2009; Stafoggia et al., 2010). Few multicity studies have addressed health effects of ozone in large regions of China due to the scarcity of ozone monitoring data (Kan et al., 2012; Wong et al., 2008).

China currently experiences severe and complex ambient air pollution. In addition to particulate pollution, ozone pollution in China is already appearing with large increases during the past two decades (Brauer et al., 2015). Since air pollution characteristics, resident health conditions, population sensitivity, and life-styles in China differ from those in developed countries (Yan et al., 2013), the concentration-response coefficients observed in developed countries may not be applicable in China. Previous studies have noted stronger associations between short-term ozone exposure and daily mortality in mainland China than those in U.S., Canada, European countries (Liu et al., 2013; Wong et al., 2008), and Japan (Chen et al., 2014).

A key issue in assessing the acute effect of short-term ozone exposure on mortality is whether a threshold exists, which plays an important role in setting ozone air quality standard (U.S. EPA, 2013).

* Corresponding authors.
E-mail addresses: jbi@nju.edu.cn (J. Bi), plk3@cumc.columbia.edu (P.L. Kinney).

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No evidence of a threshold was found in most of studies in the North America and Europe (Bell et al., 2006; Katsouyanni et al., 2009; Peng et al., 2013; Smith et al., 2009). Previous studies in several Chinese cities also found a linear relationship between ozone and mortality, suggesting no evidence of an obvious threshold (Wong et al., 2008; Yang et al., 2012). On the contrary, a reanalysis in the U.S. reported apparent thresholds in nine major U.S. cities (Stylianou and Nicolich, 2009). A recent multicity study in Japan and Korea also found a non-linear association with a clear threshold around 30–40 ppb (Bae et al., 2015). Whether a safe ozone threshold exists is also very critical in assessing the ozone-related health burden. Compared with a no threshold assumption, applying a relatively high concentration threshold (30–40 ppb) would greatly reduce the estimated ozone-related burden of premature mortality under both past and future climate change (Anenberg et al., 2010; Heal et al., 2013; Raquel et al., 2013). Given the increasing ambient ozone pollution in China and the importance of threshold assumption in assessing its health burden, more studies are needed to explore the possible presence of ozone threshold in the ozone-mortality relationship in China.

In this study, we aimed to evaluate the relationship between short-term ozone exposure and daily total mortality, and to explore the potential threshold in seven cities of Jiangsu Province, China during 2013–2014.

2. Methods

Our study area included the urban districts of seven cities in Jiangsu Province: Nanjing, Wuxi, Changzhou, Suzhou, Lianyungang, Yancheng, and Zhenjiang (Supplemental Material, Fig. S1). The total population in our study area is 25.51 million by the end of 2010.

2.1. Mortality data

Daily mortality data for each city from January 1, 2013 to December 31, 2014 were obtained from the Jiangsu Provincial Center for Disease Prevention and Control. Daily total non-accidental deaths were identified based on the International Classification of Diseases, Revision 10 (ICD-10) using codes A00-R99 for all ages. Because the mortality cases were underreported in the last three days of the year 2014 in Nanjing, these days were excluded.

2.2. Air pollution and meteorological data

Air pollution data from January 18, 2013 to December 31, 2014 in each city of Jiangsu Province were collected from the official web site of the China Environmental Monitoring Center (http://106.37.208.233:20035). A total of 42 national air quality monitoring sites were located in the seven cities (Supplemental Material, Fig. S1). The daily average concentrations of maximum 8-h average (MDA8) ozone, particulate matter with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$), particulate matter with an aerodynamic diameter of 10 mm or less (PM_{10}), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) were computed for each monitoring station from the hourly concentrations. Then, the daily concentrations from each stations within a city were averaged to derive the city-specific daily concentrations. For all seven cites during our study period, the percentage of days with missing data is 0.4% for MDA8 ozone, 6.2% for $PM_{2.5}$, 6.3% for PM_{10}, 6.2% for NO_2, and 6.2% for SO_2, respectively. Daily mean temperature (Tmean) and relative humidity (RH) values were obtained from the China Meteorological Data Sharing Service System. For urban districts without weather stations, temperature and RH data from nearest weather stations were used. There were no missing data for temperature and RH during our study period.

2.3. Statistical analysis

We used a 2-stage method to evaluate the association between short-term ozone exposure and daily total mortality in Jiangsu Province. First, estimates were calculated for each city using a time-series model; then, estimates were pooled to generate an overall effect.

Because daily mortality counts were very low, they were usually assumed to follow an over-dispersed Poisson distribution. Thus, we used a generalized additive model (GAM) with a quasi-Poisson regression to evaluate the association between ozone and total mortality in each city, while controlling the confounding effects of long-term trends, temperature, relative humidity, and day of week effect. Cubic regression spline (CRS) was used to represent the smooth terms of time trend, temperature, and relative humidity. The GAM model used the following formula:

$$\begin{aligned}\text{Log}E(Y_t) &= \beta Ozone + \gamma X + s(time,\ df) + s(Tmean,\ df) + s(RH,\ df) + DOW \\ &= \beta Ozone + COVs \end{aligned} \quad (1)$$

where $E(Y_t)$ is the expected daily mortality count at day t with $\text{Var}(Y_t) = \varphi E(Y_t)$, φ is the over-dispersion parameter; β and γ are the coefficients for ozone and pollutant X; the smooth function s captures the nonlinear relationships between the covariates (time, Tmean, and RH) and mortality; and *DOW* is the dummy variable for day of the week. As in our previous study (Chen et al., 2013), 8 degree of freedom (df) per year for time trend, 6 df for temperature, and 3 df for relative humidity were selected. As in previous multicity studies (Chen et al., 2014; Wong et al., 2008), the moving average of current-day and previous day (lag0-1) was used to represent the lag effect of short-term ozone exposure. Ozone exposure at alternative single lag days (lag0-lag3) and a four-day moving average (lag0-3) were also examined. Since the effect of temperature on daily mortality may lagged over days or weeks (Gasparrini et al., 2015), we applied different lag structures for temperature: lag0-7 (the moving average of the current-day and the previous seven days); lag0-14 (the moving average of the current-day and the previous 2 weeks); lag0-21 (the moving average of the current-day and the previous 3 weeks); lag0-28 (the moving average of the current-day and the previous 4 weeks). In addition, we also applied two separate lag structures together in the model (lag0 and lag1-3) as used in a multicity study in the U.S. (Bell et al., 2006). To select the optimal temperature lag structure, the generalized cross-validation (GCV) values was computed.

In the second stage, city-specific estimates across seven cities were combined to estimate the average risk of ozone-related mortality using a univariate random-effects meta-analysis (Gasparrini et al., 2012). This approach can flexibly pool the risk estimates while accounting for variations across cities (heterogeneity). This approach generates posterior estimates (mean and 95% intervals) for the overall effect of short-term ozone exposure on daily total mortality in Jiangsu Province. Heterogeneity among cities was assessed by the I^2 statistic, which measures the percentage of variability due to the true heterogeneity (Higgins and Thompson, 2002). Heterogeneity was considered to be significant if $I^2 > 0.5$, moderately significant if $0.25 < I^2 < 0.5$, and nonsignificant if $I^2 < 0.25$ (Chen et al., 2014).

In addition to the full-year data analysis, the modifying effects of seasonality (warm and cold) on the ozone-mortality relationship were also analyzed. The df for the time trend in the seasonal analysis was half of those from the full-year analysis, while other parameters remained the same.

We applied three approaches to evaluate whether a threshold exists in the ozone-mortality concentration-response curve. Firstly, we explored the nonlinearity in the concentration-response curve for each city using a spline approach, which also allows for a visual inspection of the existence of a safe ozone threshold. In this approach, the ozone variable in Eq. (1) was replaced by a natural cubic spline of ozone with 3 df. To compare spline models with linear models, we computed the