国家自然科学基金 北京大学管理科学数据中心

——《数据与决策》系列报告

特别鸣谢“黄廷方/信和交流发展基金”的慷慨资助

Temporal Variations in Ambient Particulate Matter Reduction Associated Short-term Mortality Risks in Guangzhou, China A Time-series Analysis (2006-2016)

我国典型地区空气质量改善的健康效益评估及人群健康防护策略研究课题组

北京大学 PEKING UNIVERSITY

国家自然科学基金 北京大学管理科学数据中心
Data Center for Management Science, NSFC-PKU

国家自然科学基金
北京大学管理科学数据中心智库

简介

国家自然科学基金—北京大学管理科学数据中心 (Data Center for Management Science, NSFC-PKU) 成立于 2014 年 12 月，是由国家自然科学基金支持，服务全国管理科学的数据收集与数据服务中心。作为北京大学直属的、以交叉学科为特点的实体学术科研机构，中心长期开展以中国家庭追踪调查（China Family Panel Studies, CFPS）、中国健康与养老追踪调查（China Health and Retirement Longitudinal Study, CHARLS）为代表的一系列大样本、高质量的微观调查数据收集。自成立以来，数据中心借助已有优势，逐步推进数据采集、数据管理与服务和智库研究三个领域的建设。

中心智库以构建开放性的、跨学科研究平台为目标，旨在大力推动运用科学的量化研究方法，以开发和利用 CFPS、CHARLS 等优质数据资源为基础的量化研究，并针对国家经济和社会管理的重大需求，积极为国家发展提供有实证依据的政策建议。

中心智库每年通过公开竞标方式，择优资助若干研究课题，为立项课题提供研究资金、研究助理和办公空间等多方面支持，并借助智库平台对相关研究成果进行推广。此外，中心智库推出客座研究员项目，诚邀有志从事与政策相关的数据研究的学者们驻中心研究。客座研究员可得到数据服务及办公条件的支持，并参与中心组织的各类学术研讨活动。

同时，中心智库通过研讨会、公开讲座等学术活动，促进知识分享和研究成果交流。中心智库还推出《数据与决策》系列出版物，包括《数据与决策：工作论文》、《数据与决策：政策报告》、《数据与决策：政策简讯》，旨在为以数据为基础的科学研究与政策研究的学者提供互动交流的平台。

目录

contents

Abstract

Numerous studies have reported associations between ambient particulate matter (PM) and daily mortality; however, little is known about temporal variations in ambient air pollution associated mortality risks, particularly in developing countries with limited long time-series air monitoring data.

In present study, we assessed the associations and temporal relationships between ambient PM and daily mortality in Guangzhou, China, during 2006-2016. With this unique 11-year dataset, we related daily concentrations of PM with aerodynamic diameter ≤ 2.5 μm (PM2.5), between 2.5 and 10 μm (PM10-2.5) and ≤ 10 μm (PM10) to daily mortality in Guangzhou. We applied overdispersed Poisson regression with adjustment for time trend and potential confounding factors. Multiple level sensitivity analyses were conducted to examine the robustness of main results.

Between 2006 and 2016, annual concentrations of PM2.5 decreased by 50.8% to 27.0 μg/m3, of PM10-2.5 by 27.6% to 16.2 μg/m3, and of PM10 by 44.1% to 43.3 μg/m3 in Guangzhou. In this study, per 10 μg/m3 increases in mean concentrations at current day and 6 prior days of death (lag06), we observed increases in total mortality risks of 0.55% (95% Confidence Interval (CI): 0.24%, 0.86%) for PM2.5, 0.99% (95%CI: 0.48%, 1.50%) for PM10-2.5, and 0.44% (95%CI: 0.22%, 0.65%) for PM10. Stronger associations were observed for ambient PM on cardio-respiratory mortality and people at age ≥ 65 years. Despite drastic reductions in annual PM levels, PM2.5 associated cardiovascular and respiratory mortality risks remained significant at 1.26% (95%CI: 0.19%, 2.35%) and 1.91% (95%CI: 0.25%, 3.60%) during 2014-2016. Further, PM2.5 and PM10 associated respiratory mortality risks showed increasing trend over time (p-value =0.03 for PM2.5).

In summary, though ambient PM levels decreased substantially in Guangzhou in recent years, PM2.5 and PM10 associated cardio-respiratory mortality risks remained significant and respiratory mortality risks even increased. Our findings provide strong rationale for continuation of ambient air pollution control effort for public health protection in the future.

Keywords: Air pollution Particulate matter Mortality Temporal variation Risk

1 Introduction

Numerous epidemiological studies worldwide have reported associations between ambient air pollution and mortality and morbidity for cardio-respiratory diseases over the decades (Di et al., 2017; Samet et al., 2000; Tao et al., 2012; Zanobetti and Schwartz 2009). With emerging evidence from global air pollution and health studies, the World Health Organization (WHO) updated the Air Quality Guidelines (AQGs) for six criteria air pollutants in 2005, aiming for air quality improvement and health risk control at a global scale (Krzyzanowski and Cohen 2008; WHO 2006). Among the six criteria air pollutants, particulate matter (PM) with aerodynamic diameter <2.5 μm ($PM_{2.5}$) and <10 μm (PM_{10}) are the primary air pollutants of health concerns, and have been shown consistent and significant associations with adverse health effects (Chen et al., 2011; Franklin et al., 2007; Lee et al., 2015; Pope et al., 2002; Wong et al., 2008).

In recent years, gradual declines in ambient air pollution levels have been achieved resulting from a series of governmental regulations and efforts on air pollution control in most Chinese cities (Bao et al., 2015; Cheng et al., 2013; Lin et al., 2014). Among these cities, air quality in Guangzhou has been improved dramatically in recent years, which is the capital city of Guangdong province locating in the center of Pearl River Delta (PRD) region. In this area, stringent air pollution control measures had been implemented for the 16th Asian Game in 2010, including transportation restrictions and emission control from industries (Ding et al., 2016; Liu et al., 2013). Further, Guangdong Air Pollution Prevention and Concentration Action Plan (GAPPCAP) was released in 2014 and under implementation since then, in which the goal of air quality improvement was specified for reducing $PM_{2.5}$ concentrations by 20% from 2012 to 2017 in Guangzhou (People's Government of Guangdong Province, 2014). Collectively, these series of efforts have resulted in large improvement in air quality in Guangzhou over the last decade (Ding et al., 2016; Jiang et al., 2015; Lin et al., 2014; Yao et al., 2012), and provided a unique opportunity for a natural experimental analysis on the temporal variations in ambient air pollution associated health risks.

Thus far, limited studies examined temporal variations in ambient air pollution concentrations and associated short-term mortality risks under air quality management framework, and the results remained inconsistent (Breitner et al., 2009; Dominici et al., 2007; Tzima et al., 2018). Dominici et al. (2007) reported the declines in PM_{10} associated total mortality risk from 1987 to 2000 in the United States, following the implementation of air pollution control policies (Dominici et al., 2007). Breitner et al. (2009) also reported reductions in mortality risks following air quality improvement between 1991 and 2002 in Erfurt, Germany (Breitner et al., 2009). However, a recent analysis from Athens, Greece during 2001-2012 reported increases in mortality risk after economic crisis in 2008, suggesting that increases in vehicular emission and consumption of heating biomass fuel might be responsible for increased toxicity of ambient PM and associated adverse health impact (Tzima et al., 2018).

We have previously reported significant increases in morality risks associated with ambient air pollution in China as well as in the PRD region (Shang et al., 2013; Tao et al., 2012; Tao et al., 2011). However, because long time-series monitoring data of air pollutants is sparse, particularly for $PM_{2.5}$ which have been routinely monitored only since 2013 in most Chinese cities, very limited research has investigated temporal variations in ambient PM associated mortality risks at a long-term scale in China. In present study, we examined temporal variations in daily mortality risks in association with ambient $PM_{2.5}$, PM with aerodynamic diameter between 2.5 and 10 μm ($PM_{10-2.5}$) and $PM_{10,}$ using a unique dataset with 11-year daily air pollution data and death counts in Guangzhou, between

2006-2016. We further assessed the impact of ambient size-fractioned PM on daily total and cardio-respiratory mortality, following a series of air quality improvement action in the area with overall and period-specific analyses.

2 Materials and methods

2.1 Study site description

We conducted the study in Guangzhou from 1 January 2006 to 31 December 2016, which is the capital city of Guangdong Province and located in central PRD region with a total registered local residents of 14.5 million in 2017. Guangzhou undergoes a typical monsoon-influenced climate with either wet and hot months or dry and cool to mild months, with seasonal variations in wind directions.

2.2 Mortality data

We obtained daily mortality counts for the years from 2006 to 2016 from Health Statistics Information Center of Guangdong Province, including identification number, sex, age, residential address, cause of death and date of death. All mortality data were reported to the death registry system and classified by International Classification of Diseases, Revision 10 (ICD-10). Following causal categories of daily mortality data were obtained: total non-accidental mortality (ICD-10 codes A00-R99), cardiovascular mortality (ICD-10 codes I00-I99) and respiratory mortality (ICD-10 codes J00-J98) for all ages, and by age (0-64 and ≥65 years) and sex (male and female).

2.3. Environment data

Ambient air pollution data during 2006-2016 were measured at two monitoring stations, including one in Wanqingsha district (22.75°N, 113.61°E) and one in Tianhu district (23.65°N, 113.62°E) (Figure S1), which were operated by Guangdong Environment Monitoring Center since early 2000's. Both monitoring stations were in the areas with mixed residential and commercial activities, and with distance to traffic and industrial sources. The air pollution monitors were at about 10-20m above ground levels and regularly maintained following standard operation procedures under China national quality control assurance plan.

We obtained hourly concentrations of $PM_{2.5}$ and PM_{10}, nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) from each monitoring station. $PM_{2.5}$ and PM_{10} were measured by tapered element oscillating microbalance (TEOM). NO_2 and SO_2 were measured using chemiluminescence and fluorescence instruments, respectively. We calculated daily concentrations for these pollutants for the days with valid measurements for at least 18 to 24h. Given that $PM_{2.5}$ was highly correlated with PM_{10} in each station with spearman correlation > 0.9 (Table S1), missing daily data of $PM_{2.5}$ or PM_{10} were imputed based on linear regressions between $PM_{2.5}$ and PM_{10} at each station. If daily data of $PM_{2.5}$ and PM_{10} were simultaneously missing on the same day, data were classified as missing values. Daily concentrations of $PM_{10-2.5}$ were calculated by subtracting daily concentrations of $PM_{2.5}$ from concurrently measured concentrations of PM_{10}. Missing data of SO_2 and NO_2 were not imputed due to < 3% missing rate. Finally, daily air pollutant concentrations at city level in Guangzhou were obtained by averaging the measurements from both monitoring stations, and used as the air pollution exposure matrix in population mortality risk assessment. Data of daily temperature and relative humidity (RH) were measured at a fix-site station locating in Liwan district of Guangzhou (23.08°N, 113.19°E), and obtained from Chinese Academy of Meteorological Sciences (Tao et al., 2012).

2.4 Statistical analysis

In this study, we applied Poisson regression analysis allowing for overdispersion to assess the associations between ambient PM and daily mortality risks, with adjustment for time trend, temperature and RH, day of the week (DOW), public holidays, influenza epidemics and annual total population (Burnett et al., 2004; Costa et al., 2017; Tao et al., 2012).

We first built basic models without including any air pollutant variables. We chose 8 degrees of freedom (DF) per year for time trend based on previous studies (Tao et al., 2012). We included smooth terms for temperature and RH on the same day of death (lag0) using natural splines function. The choice of most appropriate DF for temperature and RH was determined by minimizing Akaike's information criterion (AIC) (Rich et al., 2012). We also included smoothing term for mean of temperature on 6 prior days of death (lag16) using natural splines function if the models with this term resulted in lower AIC. The choice of DF for time trend, temperature and RH for each mortality outcome was shown in Table S2. DOW, public holidays and influenza epidemics were classified as categorical variables. We assigned 1 to influenza epidemics when the 7-day moving average of daily respiratory mortality counts was greater than the 90th percentile of its time-series distribution, or 0 otherwise. In addition, influenza epidemics was not controlled when respiratory mortality were treated as the dependent variable, because the influenza was estimated by the distribution of respiratory mortality (Samoli et al., 2013; Tao et al., 2012). We also included the logarithm of total population by year as an offset to control for impacts of demographic shifts over time (Lin et al., 2016; Qiao et al., 2015). The total annual population in Guangzhou were obtained from Guangzhou Statistical Bureau (http://www.gzstats.gov.cn/).

When basic models were defined, we included $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} separately into the models for estimating the associations with daily mortality on single-day lags (lag0 to lag6) and multiple-day lags. The multiple-day lags were defined as the mean of current day and several prior days (up to 6 days) of death (e.g. lag01 to lag06). Based on the selected lag day structures, we conducted the assessment on the associations for ambient PM on total and cause-specific mortality, and stratified the analyses by age and sex.

Further, to investigate the temporal variations in ambient PM associated mortality risks using this long time-series dataset, we conducted period-specific analyses stratified by three periods of 2006-2009, 2010-2013 and 2014-2016. We included the stratified periods as an indicator variable, as well as an interaction term for ambient PM and periods into the model. Then, we evaluated time trend in risk variations over study periods by examining the interactions at p-values <0.05 (Fischer et al., 2011).We further performed additional period-specific analysis for ambient PM associated with mortality risks by longer overlapping intervals of 4-year (e.g. 2006-2009, 2007-2010, and so on up to 2013-2016) to assess the consecutive variations in risks over long period of observations (Kim et al., 2015; Renzi et al., 2017). Further, we applied nonparametric Mann-Kendall test to assess possible trends of air pollution associated mortality risks over time (Shin et al., 2008; Xu et al., 2017).

Finally, we conducted several sensitivity analyses to investigate the robustness of associations for ambient PM on daily mortality reported in main models. We conducted two pollutant models by including NO_2 or SO_2 into the main models to investigate whether short-term mortality effects of ambient PM were partially attributed to co-generated gaseous pollutants. We also applied three alternative modeling approaches by changing covariates: firstly, we applied polynomial distributed lag (PDL) model by including a matrix of third-degree polynomial to estimate mortality risks for cumulative exposure to ambient PM (Costa et al., 2017). Secondly, we applied a case-crossover design approach with a three-way interaction between year, month, and DOW to control for time trend and seasonality (Renzi et al., 2017; Stafoggia et al., 2016). Lastly, we applied distributed lag non-linear model (DLMN) by including temperature with natural spline of 5 DFs for both exposure and lag spaces, and up to a maximum lag of 7 days (Kim et al., 2017; Qiao et al., 2015).

Preliminary analyses indicated that the largest mortality effects for ambient PM exposure were observed at lag06 day, we thus reported main results as excess risk of mortality and its 95% confidence intervals (CIs) in association with 10 $\mu g/m^3$ increase in ambient PM concentrations at lag06 day. We also used an interquartile range (IQR) increment to account for the absolute change of ambient PM concentration. All analyses were performed in R, version 3.4.2 (R Project for Statistical Computing, Vienna, Austria), using the “mgcv”, “dlnm” and “Kendall” packages, (the Comprehensive R Archive Network (CRAN) at http://cran.r-project.org). Statistical significance was defined as $p<0.05$.

3 Results

Table 1 provides the summary statistics of daily death counts, air pollutant concentrations and meteorological variables in Guangzhou, 2006-2016. During study period, the total non-accidental death counts were 430,565, including 163,825 for cardiovascular diseases and 72,370 for respiratory diseases. The average daily death counts were 107.7 for total mortality, of which 60.9 were males and 80.9 were age ≥65 years. Daily death counts increased slightly over time as shown in Figure S2. Average daily concentrations were 40.5 μg/m^3 for $PM_{2.5}$, 19.9 μg/m^3 for $PM_{10-2.5}$, 59.7 μg/m^3 for PM_{10}, 25.7 μg/m^3 for NO_2 and 27.0 μg/m^3 for SO_2. Among daily air pollutant concentrations and meteorological variables, PM_{10} was highly correlated with $PM_{2.5}$ and $PM_{10-2.5}$ (correlation coefficients of 0.95 and 0.84), whereas NO_2 and SO_2 moderately correlated with $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} (correlation coefficients ranged from 0.50 to 0.63). Temperature and RH were negatively correlated with air pollutants (Table S3).

Figure 1 presents the variations in annual averages of daily concentrations for $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} in Guangzhou during 2006-2016, showing the decreasing trends of ambient PM levels over time. In specific, from 2006 to 2016, annual concentrations decreased for $PM_{2.5}$ by 50.8% to 27.0 μg/m^3 (corresponding to 28.0 μg/m^3 reduction), for $PM_{10-2.5}$ by 27.6% (6.2 μg/m^3 reduction), and for PM_{10} by 44.1% (34.2 μg/m^3 reduction). Ever since 2015, both annual levels of $PM_{2.5}$ and PM_{10} in Guangzhou have been below Chinese National Ambient Air Quality Standard of 35 μg/m^3 for $PM_{2.5}$ and 70 μg/m^3 for PM_{10}, which indicated dramatic air quality improvement in the area in recent years.

Associations between ambient PM and mortality outcomes over the entire study period are shown in Figure S3. The associations for ambient PM at lag06 on total and cardio-respiratory mortality, as well as in age- and sex-specific groups, are summarized in Table 2. In specific, a 10 μg/m^3 increase was associated with significant increases in total mortality of 0.55% (95%CI: 0.24%, 0.86%) for $PM_{2.5}$, 0.99% (95%CI: 0.48%, 1.50%) for $PM_{10-2.5}$ and 0.44% (95%CI: 0.22%, 0.65%) for PM_{10}. Stronger associations with $PM_{2.5}$ and PM_{10} exposure were observed for cardio-respiratory mortality. Further, stronger associations in elderly group (≥65 years) than those in younger age group (0-64 years) (e.g. 0.71% (95%CI: 0.35%, 1.06%) in elderly group and 0.16% (95%CI: -0.37%, 0.69%) in younger age group for 10 μg/m^3 increase in $PM_{2.5}$), as well as respiratory mortality in females (e.g. 1.47% (95%CI: 0.47%, 2.49%) for 10 μg/m^3 increase in $PM_{2.5}$) and cardiovascular mortality in males (e.g. 1.50% (95%CI: 0.88%, 2.12%) for 10 μg/m^3 increase in $PM_{2.5}$).

For period stratified analyses, Table 3 presents continuous and significant decreases in ambient PM concentrations during periods of 2006-2009, 2010-2013 and 2014-2016 in Guangzhou, with similar ratios of period means for ambient PM over periods (ranged from 1.15 to 1.35). Table S5 presents daily, annual mortality counts and mortality rate in Guangzhou during three time periods. Daily total mortality counts increased continuously from 97.8 to 120.5 from 2006-2009 to 2014-2016, as well as from 34.1 to 48.6 and from 16.5 to 18.7 for cardiovascular and respiratory mortality correspondingly. Annual mortality rate of each mortality outcome remained relative consistent across three time periods.

Table 4 presents the period-specific risk estimates associated with 10 μg/m^3 and IQR increase in $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} for the periods of 2006-2009, 2010-2013 and 2014-2016. With annual averages in ambient PM decreased over study period, the associations between ambient PM and total mortality were non-significant in recent years (2014-2016); however, $PM_{2.5}$ and PM_{10} associated cardio-respiratory mortality risks remained significant. In specific, a 10 μg/m^3 increase was associated with increases in cardiovascular mortality of 1.26% (95%CI: 0.19%, 2.35%) for $PM_{2.5}$, and 0.91% (95%CI: 0.16%, 1.66%) for PM_{10}. Moreover, we found that the associations for $PM_{2.5}$ and PM_{10} on respiratory mortality showed increasing trend over time. Specifically, we observed that a 10 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with increases in respiratory mortality of 0.39% (95%CI: -0.66%, 1.46%) in the period of 2006-2009, 1.12% (95%CI: 0.05%, 2.20%) in 2010-2013, and 1.91% (95%CI: 0.25%, 3.60%) in 2014-2016 (p-trend=0.03). Similar trend for risks for PM_{10} on respiratory mortality (p-trend=0.02). Additional period-specific analysis by overlapping 4-year intervals also showed that risk estimates remained significant in recent years, except for total and respiratory mortality during 2013-2016 (Figure 2). Mann-Kendall test for time varying risk estimates also indicated that potential increases in $PM_{2.5}$ and PM_{10} associated respiratory mortality and $PM_{10-2.5}$ associated cardiovascular mortality risks in recent years ($p<0.05$, Table S4). Further, period-specific results in age- and sex-specific groups are shown in Table S6-S8. We also found that $PM_{2.5}$ and PM_{10} associated respiratory mortality remained significant in population at age ≥65 years in recent years, and with an increasing trend across three time periods (p-trend <0.05). Whereas, $PM_{10-2.5}$ and PM_{10} associated respiratory mortality risks also showed increases though without statistical significance.

In two pollutant model analyses with adjustment for NO_2 or SO_2, ambient PM associated mortality risks remained robust and significant in main results (Table 5), as well as in period-specific analyses which confirmed the increasing trend in respiratory mortality risks in association with $PM_{2.5}$ and PM_{10} over time periods (Table S9). Mortality risks explored in other models including PDL models, case-crossover analyses and DLNM models remained consistent with the main results (Table S10).

4 Discussion

In present study, we investigated temporal variations in short-term mortality risks in association with $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} in Guangzhou, China during 2006-2016. This is the first analysis to investigate temporal trends in ambient PM associated mortality risks over a long time scale in China, using monitoring measurements. Between 2006 and 2016, annual average concentrations decreased by 50.8% for $PM_{2.5}$, 27.6% for $PM_{10-2.5}$, and 44.1% for PM_{10}. However, ambient PM associated total and cardio-respiratory mortality risks remained significant in the area during study period, and stronger associations were observed in population at age ≥65 years. Further, despite drastic reduction in ambient PM concentrations in recent years, cardio-respiratory mortality risks in association with $PM_{2.5}$ and PM_{10} remained significant, and respiratory mortality risks even increased over time,

In present study, we observed substantial reductions in concentrations of $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} in Guangzhou from 2006 to 2016, suggesting effective air quality control measures in the area in recent years. Consistently, Ma et al. (2016) observed a decrease trend in $PM_{2.5}$ concentrations during 2008-2013 in PRD region (Ma et al., 2016). One study simulated changes in air pollutants during the Asian Game in Guangzhou, and reported 17.1% and 21.5% reductions in concentrations of $PM_{2.5}$ and PM_{10}, respectively (Liu et al., 2013). Furthermore, Jiang et al. (2015) evaluated the achievable air quality improvement under GAPPCAP regulation in PRD region, and predicted that concentrations of $PM_{2.5}$ could be reduced by 17% during 2012-2017 (Jiang et al., 2015).

This long time-series analysis confirmed the consolidated epidemiological evidence on the effects of ambient PM on daily mortality at a global scale, and the magnitude of associations for $PM_{2.5}$ and PM_{10} on mortality outcomes observed in present study were generally comparable with those reported in previous studies (Breitner et al., 2009; Chen et al., 2017; Di et al., 2017; Samoli et al., 2013; Zanobetti and Schwartz 2009). A national analysis including US 112 cities reported that increases of 0.98% in total mortality, 0.85% in cardiovascular mortality and 1.68% in respiratory mortality were in association with 10 μg/m^3 increase in $PM_{2.5}$ (Zanobetti and Schwartz 2009). An analysis in 10 Mediterranean metropolitan areas reported that per 10 μg/m^3 increase in PM_{10} was significantly associated with increases in mortality of 0.32% in total mortality, 0.54% in cardiovascular mortality, and 1.12% in respiratory mortality (Samoli et al., 2013). Moreover, a study including 272 Chinese cities also showed significant increases of 0.22% in total mortality, 0.27% in cardiovascular mortality and 0.29% in respiratory mortality were associated with 10 μg/m^3 increase in $PM_{2.5}$ (Chen et al., 2017); however, the associations were generally lower than those observed in this study.

For $PM_{10-2.5}$ associated mortality risks, our results were somewhat inconsistent with those reported elsewhere (Adar et al., 2014; Chen et al., 2011; Cheng et al., 2016; Lee et al., 2015; Meister et al., 2012; Samoli et al., 2013; Zanobetti and Schwartz 2009). A study conducted in three Chinese cities reported that per 10 μg/m^3 increase in $PM_{10-2.5}$ was associated with increases of 0.25% (95%CI: 0.08%, 0.42%) in total mortality, 0.25% (95%CI: 0.10%, 0.40%) in cardiovascular mortality and 0.48% (95%CI; 0.20%, 0.76%) in respiratory mortality (Chen et al., 2011). A study in 10 European metropolitan areas found that $PM_{10-2.5}$ was associated with increases in mortality but not with statistical significance. In specific, they observed that increases of 0.3% (95%CI: -0.1%, 0.69%) in total mortality, 0.33% (95%CI: -0.78%, 1.46%) in cardiovascular morality, and 0.76% (95% CI: -0.7%, 2.25%) in respiratory mortality in association with a 10 μg/m^3 increase in $PM_{10-2.5}$ (Samoli et al., 2013). The observed disparities in associations might be due to the heterogeneity in substances adsorbed on $PM_{10-2.5}$ that can differ across regions (Zanobetti and Schwartz 2009). Moreover,

$PM_{10-2.5}$ was obtained as the difference between PM_{10} and $PM_{2.5}$, which could also introduce errors resulted from measurements for PM_{10} and $PM_{2.5}$ (Stafoggia et al., 2013).

In age and sex stratified analyses in this study, stronger associations were observed in elderly people, which are largely consistent with previous findings (Franklin et al., 2007; Lee et al., 2015; Samoli et al., 2013), and confirmed that elderly people are more susceptible to air pollution. We also observed that females were at greater respiratory mortality risk in association with ambient PM, whereas males were at greater cardiovascular mortality risk. One possible explanation might be the differences in time-activity pattern and occupational exposure between sexes, in which males tend to spend more time outdoors and conduct more physical activities which might result in greater accumulative air pollution exposure (Dong et al., 2013). Other possibilities might include the disparities in lung architecture and gas-blood barriers permeability that could result in differences in vascular transport and organ accumulation from inhalation of toxic mixture in the ambient (Dong et al., 2013; Faustini et al., 2011; Franklin et al., 2007).

Though ambient PM levels reduced greatly over time in Guangzhou, our analyses showed that the mortality risks in association with $PM_{2.5}$ and PM_{10} remained significant with some increases in recent years, particularly for respiratory mortality. Several studies conducted in the cities in developed countries have also investigated temporal variations in short-term mortality risks in association with ambient air pollution, however the findings were not completely consistent with present study (Breitner et al., 2009; Dominici et al., 2007; Kim et al., 2015; Renzi et al., 2017; Tzima et al., 2018). A recent study conducted in Athens during 2001-2012 and a study in Seoul during 2001-2011 reported that despite reduction of ambient PM concentration, the associated mortality risks showed increased over time (Kim et al., 2015; Tzima et al., 2018). However, a study conducted in Germany found ambient air pollution associated mortality risks decreased following air pollution control measures implementation during 1995-2002 (Breitner et al., 2009). Moreover, a study conducted in Rome during 2001-2014 and another study conducted in Switzerland during 2001-2010 both reported that PM_{10} associated short-term mortality risks did not vary significantly over time, as concentrations of PM_{10} decreased substantially (Perez et al., 2015; Renzi et al., 2017). Nevertheless, the inconsistencies in findings across studies might result from the differences in sources and chemical compositions of ambient air pollution and population size across study areas (Shang et al., 2013; Tzima et al., 2018).

In this study, the observed increases in mortality risks in the area in recent years might be explained by the changes in components in PM mixture over time. Fu et al. (2014) assessed the trends in chemical components of $PM_{2.5}$ in PRD region between 2007 and 2011, and reported the increases in NO_x emissions from vehicles in recent years, which might introduce potential alternations in atmospheric oxidizing capacity with sequential impact on aerosol toxicity (Fu et al., 2014). Possible transitions in population characteristics might also exaggerate time-varying mortality risks in population (such as aging, prevalence of chronic diseases) (Kim et al., 2015). In Guangzhou, the proportion of population at age ≥65 years increased from 6.62% in 2005 to 7.90% in 2015 (Guangzhou Statistical Bureau). Thus, population aging might also contribute to the increases in cardio-respiratory mortality risks in association with $PM_{2.5}$ and PM_{10} at population level. More information on ambient PM speciation and source changes over time, as well as detailed demographic data including aging, smoking and living habits would be important in further studies to address the changes in ambient PM associated mortality risks in the area.

Despite that a unique 11-year time-series dataset of air pollution and daily mortality was used in this sophisticate analysis, study limitations should also be noted. Firstly, time-series ecological design including measurement errors might be inherent in present study and result in potential confounding effects to bias the estimates. Secondly, the air pollution data obtained from two air monitoring stations might not well represent exposure for total population, and limited number of air monitoring stations for exposure assessment might yield biased variance in effect estimates and resulted in inefficient significances in effect estimates.

5 Conclusions

Our results showed substantial decreases in annual averages of $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} in Guangzhou, during 2006-2016; however, overall associations for ambient PM on mortality were significant, and people at age ≥65 years were at greater risks. Moreover, $PM_{2.5}$ and PM_{10} associated cardio-respiratory mortality risks remained significant in recent years, and respiratory mortality risks even showed increases over time. Our findings suggest further investigation on temporal and spatial variations in short-term mortality risks in association with ambient air pollution in China, and continuation on air pollution control effort for public protection in the future.

Declarations of interest

None

Acknowledgement

This study was supported by National Natural Science Foundation of China-Peking University (NSFC-PKU) Data Center for Management Science (2017KEY05); National Natural Science Foundation of China (81773381, 41425020, 91644215); and Ministry of Environmental Protection of the People's Republic of China Fund for National Environmental Criteria Management (2110105).

References

Adar, S.D., Filigrana, P.A., Clements, N., Peel, J.L., 2014. Ambient Coarse Particulate Matter and Human Health: A Systematic Review and Meta-Analysis. Curr. Environ. Health Rep. 1,258-274.

Bao, J., Yang, X., Zhao, Z., Wang, Z., Yu, C., Li, X., 2015. The Spatial-Temporal Characteristics of Air Pollution in China from 2001–2014. Int J Environ. Res. Public Health 12,15875-15887.

Breitner, S., Stölzel, M., Cyrys, J., Pitz, M., Wölke, G., Kreyling, W., Küchenhoff, H., Heinrich, J., Wichmann, H.E., Peters, A., 2009. Short-Term Mortality Rates during a Decade of Improved Air Quality in Erfurt, Germany. Environ. Health Perspect. 117,448-454.

Burnett, R.T., Stieb DBrook, J.R., Cakmak, S., Dales, R., Raizenne, M., Vincent, R., Dann, T., 2004. Associations between short-term changes in nitrogen dioxide and mortality in Canadian cities. Arch. Environ. Health 59,228-236.

Chen, R., Li, Y., Ma, Y., Pan, G., Zeng, G., Xu, X., Chen, B., Kan, H., 2011. Coarse particles and mortality in three Chinese cities: the China Air Pollution and Health Effects Study (CAPES). Sci. Total Environ. 409,4934-4938.

Chen, R., Yin, P., Meng, X., Liu, C., Wang, L., Xu, X., Ross, J.A., Tse, L.A., Zhao, Z., Kan, H.,

2017. Fine Particulate Air Pollution and Daily Mortality: A Nationwide Analysis in 272 Chinese Cities. Am. J. Respir. Cri. Care. Med. 196,73-81.

Cheng, M.H., Chiu, H.F., Yang, C.Y., 2016. The Effects of Coarse Particles on Daily Mortality: A Case-Crossover Study in a Subtropical City, Taipei, Taiwan. Int. J. Environ. Res. Public Health 13,347.

Cheng, Z., Jiang, J., Fajardo, O., Wang, S., Hao, J., 2013. Characteristics and health impacts of particulate matter pollution in China (2001–2011). Atmos. Environ. 65,186-194.

Costa, A.F., Hoek, G., Brunekreef, B., Ponce de Leon, A.C., 2017. Air Pollution and Deaths among Elderly Residents of Sao Paulo, Brazil: An Analysis of Mortality Displacement. Environ. Health Perspect. 125,349-354.

Di, Q., Wang, Y., Zanobetti, A., Wang, Y., Koutrakis, P., Choirat, C., Dominici, F., Schwartz, J.D., 2017. Air Pollution and Mortality in the Medicare Population. N. Engl. J. Med. 376,2513-2522.

Ding, D., Zhu, Y., Jang, C., Lin, C.J., Wang, S., Fu, J., Gao, J., Deng, S., Xie, J., Qiu, X., 2016. Evaluation of health benefit using BenMAP-CE with an integrated scheme of model and monitor data during Guangzhou Asian Games. J. Environ. Sci. (China) 42,9-18.

Dominici, F., Peng, R.D., Zeger, S.L., White, R.H., Samet, J.M., 2007. Particulate air pollution and mortality in the United States: did the risks change from 1987 to 2000? Am. J. Epidemiol. 166,880-888.

Dong, G.-H., Qian, Z., Wang, J., Chen, W., Ma, W., Trevathan, E., Xaverius, P.K., DeClue, R., Wiese, A., Langston, M., Liu, M.-M., Wang, D., Ren, W.-H., 2013. Associations between ambient air pollution and prevalence of stroke and cardiovascular diseases in 33 Chinese communities. Atmos. Environ. 77,968-973

Faustini, A., Stafoggia, M., Berti, G., Bisanti, L., Chiusolo, M., Cernigliaro, A., Mallone, S., Primerano, R., Scarnato, C., Simonato, L., Vigotti, M.A., Forastiere, F., EpiAir Collaborative, G., 2011. The relationship between ambient particulate matter and respiratory mortality: a multi-city study in Italy. Eur. Respir. J. 38,538-547.

Fischer, P.H., Marra, M., Ameling, C.B., Janssen, N., Cassee, F.R., 2011. Trends in relative risk estimates for the association between air pollution and mortality in The Netherlands, 1992-2006. Environ. Res. 111,94-100.

Franklin, M., Zeka, A., Schwartz, J., 2007. Association between PM2.5 and all-cause and specific-cause mortality in 27 US communities. J Expo Sci. Environ. Epidemiol. 17,279-287.

Fu, X., Wang, X., Guo, H., Cheung, K., Ding, X., Zhao, X., He, Q., Gao, B., Zhang, Z., Liu, T., Zhang, Y., 2014. Trends of ambient fine particles and major chemical components in the Pearl River Delta region: observation at a regional background site in fall and winter. Sci. Total Environ. 497-498,274-281.

Jiang, X., Hong, C., Zheng, Y., Zheng, B., Guan, D., Gouldson, A., Zhang, Q., He, K., 2015. To what extent can China's near-term air pollution control policy protect air quality and human health? A case study of the Pearl River Delta region. Environ. Res. Lett. 10,104006.

Kim, H., Bell, M.L., Lee, J.T., 2017. Does a lag-structure of temperature confound air pollution-lag-response relation? Simulation and application in 7 major cities, Korea (1998-2013). Environ. Res. 159,531-538.

Kim, H., Kim, H., Lee, J.T., 2015. Effects of ambient air particles on mortality in Seoul: Have the effects changed over time? Environ. Res. 140,684-690.

Krzyzanowski, M., Cohen, A., 2008. Update of WHO air quality guidelines. Air Quality. Atmos. Health 1,7-13.

Lee, H., Honda, Y., Hashizume, M., Guo, Y.L., Wu, C.F., Kan, H., Jung, K., Lim, Y.H., Yi, S., Kim, H., 2015. Short-term exposure to fine and coarse particles and mortality: A multicity time-series study in East Asia. Environ. Pollut. 207,43-51.

Lin, H., Tao, J., Du, Y., Liu, T., Qian, Z., Tian, L., Di, Q., Rutherford, S., Guo, L., Zeng, W., Xiao, J., Li, X., He, Z., Xu, Y., Ma, W., 2016. Particle size and chemical constituents of ambient particulate pollution associated with cardiovascular mortality in Guangzhou, China. Environ. Pollut. 208,758-766.

Lin, H., Zhang, Y., Liu, T., Xiao, J., Xu, Y., Xu, X., Qian, Z., Tong, S., Luo, Y., Zeng, W., Ma, W., 2014. Mortality reduction following the air pollution control measures during the 2010 Asian Games. Atmos. Environ. 91,24-31.

Liu, H., Wang, X., Zhang, J., He, K., Wu, Y., Xu, J., 2013. Emission controls and changes in air quality in Guangzhou during the Asian Games. Atmos. Environ. 76,81-93.

Ma, Z., Hu, X., Sayer, A.M., Levy, R., Zhang, Q., Xue, Y., Tong, S., Bi, J., Huang, L., Liu, Y., 2016. Satellite-Based Spatiotemporal Trends in PM2.5 Concentrations: China, 2004-2013. Environ. Health Perspect. 124,184-192.

Meister, K., Johansson, C., Forsberg, B., 2012. Estimated short-term effects of coarse particles on daily mortality in Stockholm, Sweden. Environ. Health Perspect. 120,431-436.

People's Government of Guangdong Province, 2014. [Guangdong Air Pollution Prevention and Control Action Plan (2014–2017)]. Avaiable at : http://zwgk.gd.gov.cn/006939748/201402/t20140214_467051.html. [accessed 19 April

2018].

Perez, L., Grize, L., Infanger, D., Kunzli, N., Sommer, H., Alt, G.M., Schindler, C., 2015. Associations of daily levels of PM10 and NO2 with emergency hospital admissions and mortality in Switzerland: Trends and missed prevention potential over the last decade. Environ. Res. 140,554-561.

Pope, C.A., 3rd, Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287,1132-1141.

Qiao, Z., Guo, Y., Yu, W., Tong, S., 2015. Assessment of Short- and Long-Term Mortality Displacement in Heat-Related Deaths in Brisbane, Australia, 1996-2004. Environ. Health Perspect. 123,766-772.

Renzi, M., Stafoggia, M., Faustini, A., Cesaroni, G., Cattani, G., Forastiere, F., 2017. Analysis of Temporal Variability in the Short-term Effects of Ambient Air Pollutants on Nonaccidental Mortality in Rome, Italy (1998-2014). Environ. Health Perspect. 125,067019.

Rich, D.Q., Kipen, H.M., Huang, W., Wang, G., Wang, Y., Zhu, P., Ohman-Strickland, P., Hu, M., Philipp, C., Diehl, S.R., Lu, S.E., Tong, J., Gong, J., Thomas, D., Zhu, T., Zhang, J.J., 2012. Association between changes in air pollution levels during the Beijing Olympics and biomarkers of inflammation and thrombosis in healthy young adults. JAMA 307,2068-2078.

Samet, J.M., Zeger, S.L., Dominici, F., Curriero, F., Coursac, I., Dockery, D.W., Schwartz, J., Zanobetti, A., 2000. The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and mortality from air pollution in the United States. Res. Rep. Health Eff. Inst. 94,5-70, (discussion 71-79).

Samoli, E., Stafoggia, M., Rodopoulou, S., Ostro, B., Declercq, C., Alessandrini, E., Diaz, J., Karanasiou, A., Kelessis, A.G., Le Tertre, A., Pandolfi, P., Randi, G., Scarinzi, C., Zauli-Sajani, S., Katsouyanni, K., Forastiere, F., 2013. Associations between fine and coarse particles and mortality in Mediterranean cities: results from the MED-PARTICLES project. Environ. Health Perspect. 121,932-938.

Shang, Y., Sun, Z., Cao, J., Wang, X., Zhong, L., Bi, X., Li, H., Liu, W., Zhu, T., Huang, W., 2013. Systematic review of Chinese studies of short-term exposure to air pollution and daily mortality. Environ. Int. 54,100-111.

Shin, H.H., Stieb, D.M., Jessiman, B., Goldberg, M.S., Brion, O., Brook, J., Ramsay, T., Burnett, R.T., 2008. A temporal, multicity model to estimate the effects of short-term exposure to ambient air pollution on health. Environ. Health Perspect. 116,1147-1153.

Stafoggia, M., Samoli, E., Alessandrini, E., Cadum, E., Ostro, B., Berti, G., Faustini, A., Jacquemin, B., Linares, C., Pascal, M., Randi, G., Ranzi, A., Stivanello, E., Forastiere, F., Group, M.-P.S., 2013. Short-term associations between fine and coarse particulate matter and hospitalizations in Southern Europe: results from the MED-PARTICLES project. Environ. Health Perspect. 121,1026-1033.

Tao, Y., Huang, W., Huang, X., Zhong, L., Lu, S.E., Li, Y., Dai, L., Zhang, Y., Zhu, T., 2012. Estimated acute effects of ambient ozone and nitrogen dioxide on mortality in the Pearl River Delta of southern China. Environ. Health Perspect. 120,393-398.

Tao, Y., Zhong, L., Huang, X., Lu, S.E., Li, Y., Dai, L., Zhang, Y., Zhu, T., Huang, W., 2011. Acute mortality effects of carbon monoxide in the Pearl River Delta of China. Sci. Total Environ. 410-411,34-40.

Tzima, K., Analitis, A., Katsouyanni, K., Samoli, E., 2018. Has the risk of mortality related to short-term exposure to particles changed over the past years in Athens, Greece? Environ. Int. 113,306-312.

WHO, 2006. Air Quality Guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Global update 2005. Summary of risk assessment. World Health Organization. Avaible at: http://www.who.int/phe/health_topics/outdoorair_aqg/en/index.html. [accessed 19 April 2018].

Wong, C.M., Vichit-Vadakan, N., Kan, H., Qian, Z., 2008. Public Health and Air Pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality. Environ. Health Perspect. 116,1195-1202.

Xu, H., Ho, S.S., Cao, J., Guinot, B., Kan, H., Shen, Z., Ho, K.F., Liu, S., Zhao, Z., Li, J., Zhang, N., Zhu, C., Zhang, Q., Huang, R., 2017. A 10-year observation of PM2.5-bound nickel in Xi'an, China: Effects of source control on its trend and associated health risks. Sci. Rep. 7,41132.

Yao, Z., Zhang, Y., Shen, X., Wang, X., Wu, Y., He, K., 2012. Impacts of temporary traffic control measures on vehicular emissions during the Asian Games in Guangzhou, China. J. Air Waste Manag. Assoc. 63,11-19.

Zanobetti, A., Schwartz, J., 2009. The Effect of Fine and Coarse Particulate Air Pollution on Mortality: A National Analysis. Environ. Health Perspect. 117,898-903.

List of Figures

Figure Legends

Figure 1. Temporal trends in annual concentrations of $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} in Guangzhou, China, 2006-2016.

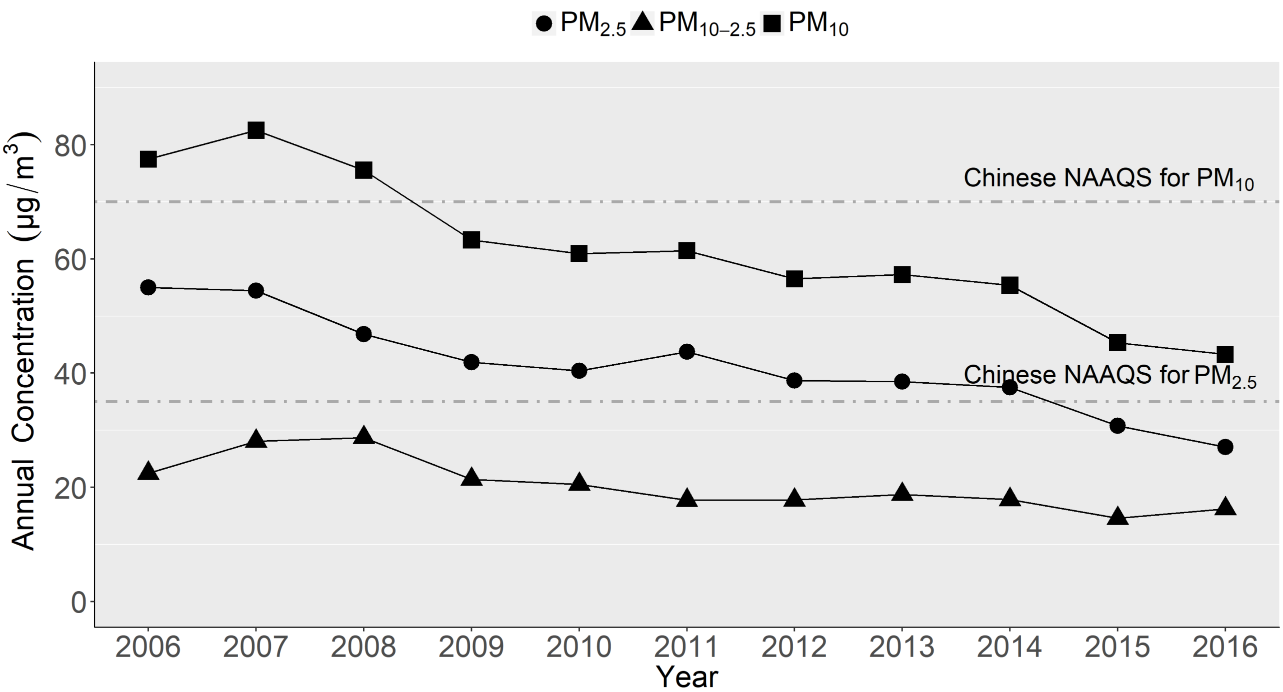
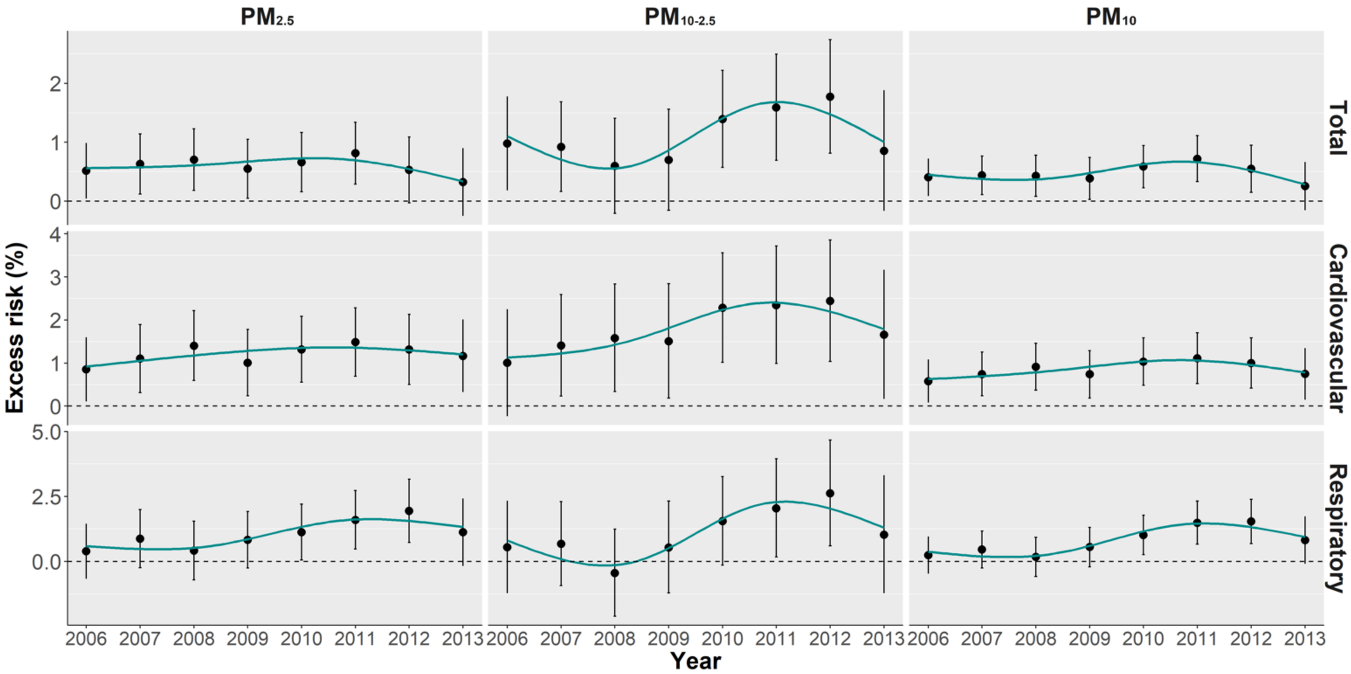


Figure 2. Temporal variations in excess risks % (95% CI) of mortality associated with each 10 $\mu g/m^3$ increases in $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} (lag06) in period-specific analyses of overlapping 4-year intervals in Guangzhou, China, 2006-2016. The curves represent mortality risks smoothed by splines function of 3 DF.



PM2.5
PM10-2.5
PM10
Total
Cardiovascular
Respiratory
Excess risk (%)
Year
2006
2007
2008
2009
2010
2011
2012
2013

List of Tables

Table 1. Summary statistics of daily death counts, air pollutant concentrations, and meteorological variables in Guangzhou, China, 2006-2016.

			Percentile				
Mortality	Sum of deaths (n)	Mean±SD	Min	25th	50th	75th	Max
Total (non-accidental)							
All	430565	107.7±21.9	55	92	105	121	228
Male	243321	60.9±13.0	24	52	60	69	122
Female	187239	46.9±11.3	17	39	46	54	106
0-64 years	109210	27.3±6.4	11	23	27	31	52
≥65 years	323255	80.9±18.5	36	68	78	91	187
Cardiovascular							
All	163825	41±12.3	12	32	41	48	105
Male	85960	21.5±6.9	4	17	21	25	52
Female	77861	19.5±7.0	4	15	19	23	54
0-64 years	28383	7.1±2.9	0	5	7	9	21
≥65 years	135442	33.9±11.0	9	26	32	40	95
Respiratory							
All	72370	18.1±6.1	5	14	17	22	48
Male	41137	10.3±4.1	0	7	10	13	29
Female	31233	7.8±3.4	0	5	7	10	24
0-64 years	6546	1.6±1.3	0	1	1	2	7

≥65 years	65824	16.5±5.8	3	12	16	20	44
Air pollutants	Num. of days (n)						
$PM_{2.5}$(μg/m^3)	3921	40.5±24.5	2.7	22.1	35.3	53.5	263.8
$PM_{10-2.5}$(μg/m^3)	3917	19.9±13.9	0.1	11.0	16.9	25.2	223.3
PM_{10}(μg/m^3)	3823	59.7±34.9	2.0	34.2	52.0	78.5	343.8
NO_2(μg/m^3)	3882	25.7±16.2	0.1	14.6	23.0	33.2	157.9
SO_2(μg/m^3)	3931	27.0±20.7	0.2	12.0	20.3	35.9	154.8
Meteorological variables							
Temperature (°C)	3996	22.3±6.3	3.4	17.8	23.9	27.4	33.5
RH (%)	3996	75.7±12.4	25.0	68.0	75.7	85.0	100.0

Abbreviations: SD, Standard deviation; $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10}, Particulate matter with an aerodynamic diameter less than or equal to 2.5 μm, 2.5~10 μm and 10 μm; NO_2, Nitrogen dioxide; SO_2, Sulphur dioxide; RH, relative humidity.

Table 2 Excess risk % (95% CI) [a] of mortality associated with 10 μg/m^3 increases in $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} (lag06) in Guangzhou, China, 2006-2016.

Mortality	Excess risk (95%CI)		
	$PM_{2.5}$	$PM_{10-2.5}$	PM_{10}
Total(non-accidental)			
All	0.55(0.24,0.86)	0.99(0.48,1.50)	0.44(0.22,0.65)
Male	0.47(0.08,0.85)	1.02(0.38,1.67)	0.41(0.14,0.68)
Female	0.67(0.24,1.10)	0.97(0.26,1.68)	0.48(0.18,0.78)
0-64 years	0.16(-0.37,0.69)	0.23(-0.67,1.14)	0.07(-0.30,0.44)
≥65 years	0.71(0.35,1.06)	1.27(0.69,1.85)	0.57(0.33,0.82)
Cardiovascular			
All	1.15(0.68,1.62)	1.64(0.86,2.43)	0.82(0.49,1.14)
Male	1.50(0.88,2.12)	2.21(1.17,3.25)	1.09(0.66,1.52)
Female	0.81(0.15,1.46)	1.10(0.03,2.19)	0.48(0.18,0.78)
0-64 years	1.03(0.01,2.06)	-0.03(-1.73,1.69)	0.40(-0.30,1.20)
≥65 years	1.18(0.67,1.70)	2.01(1.16,2.87)	0.91(0.55,1.27)
Respiratory			
All	0.78(0.10,1.46)	0.75(-0.35,1.85)	0.56(0.09,1.03)
Male	0.20(-0.68,1.10)	0.09(-1.35,1.54)	0.18(-0.43,0.78)
Female	1.47(0.47,2.49)	1.59(-0.03,3.25)	1.02(0.33,1.72)
0-64 years	-1.22(-3.35,0.96)	-1.11(-4.67,2.58)	-0.89(-2.38,0.62)
≥65 years	0.97(0.26,1.68)	0.91(-0.24,2.06)	0.70(0.21,1.19)

[a] Results from Poisson regression models, adjusted by time trend, temperature, RH, DOW, public holidays, influenza epidemics and annual total population.

Table 3. Descriptive statistics of ambient PM in Guangzhou, China, 2006-2016, stratified for three periods.

Pollutant	Period	Number	Mean±SD	Median	Ratio of period means	
					1/2[a]	2/3[b]
$PM_{2.5}$	2006-2009	1453	49.4±27.4	43.5	1.22*	1.27*
	2010-2013	1418	40.3±23.2	37.1		
	2014-2016	1046	31.8±16.0	29.4		
$PM_{10-2.5}$	2006-2009	1436	25.2±15.5	21.2	1.35*	1.15*
	2010-2013	1345	18.7±14.4	16.9		
	2014-2016	1042	16.2±8.4	15.0		
PM_{10}	2006-2009	1453	74.2±39.5	65.6	1.26*	1.23*
	2010-2013	1422	59.0±32.7	54.1		
	2014-2016	1046	48.0±22.4	45.0		

[a] 1: 2006-2009; 2: 2010-2013; [b] 3: 2014-2016
* Statistically significant (t-test, $p<0.05$)

Table 4 Excess risk % (95% CI) [a] of mortality associated with 10 μg/m^3 and IQR increases in $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} (lag06) for different time periods in Guangzhou, China, 2006-2016.

Pollutant	Mortality	10 μg/m^3 increase			IQR increase			p-trend[a]
		2006-2009	2010-2013	2014-2016	2006-2009	2010-2013	2014-2016	
$PM_{2.5}$	Total	0.51(0.04,0.99)	0.66(0.16,1.17)	0.58(-0.15,1.31)	1.50(0.12,2.89)	1.66(0.40,2.93)	1.10(-0.29,2.51)	0.73
	Cardiovascular	0.85(0.11,1.60)	1.32(0,55,2.08)	1.26(0.19,2.35)	2.50(0.32,4.72)	3.31(1.39,5.27)	2.41(0.35,4.51)	0.54
	Respiratory	0.39(-0.66,1.46)	1.12(0.05,2.20)	1.91(0.25,3.60)	1.14(-1.91,4.29)	2.81(0.12,5.57)	3.66(0.48,6.95)	0.03
$PM_{10-2.5}$	Total	0.98(0.18,1.78)	1.39(0.57,2.22)	1.01(-0.27,2.31)	1.36(0.26,2.48)	1.62(0.66,2.58)	0.93(-0.25,2.12)	0.83
	Cardiovascular	1.00(-0.23,2.25)	2.28(1.02,3.56)	2.00(0.13,3.91)	1.40(-0.32,3.14)	2.65(1.18,4.14)	1.84(0.12,3.59)	0.44
	Respiratory	0.54(-1.22,2.33)	1.55(-0.14,3.26)	1.76(-1.06,4.67)	0.75(-1.69,3.25)	1.80(-0.16,3.79)	1.62(-0.98,4.29)	0.16
PM_{10}	Total	0.40(0.08,0.72)	0.59(0.23,0.94)	0.47(-0.04,0.98)	1.77(0.37,3.18)	2.03(0.79,3.30)	1.18(-0.11,2.50)	0.67
	Cardiovascular	0.58(0.08,1.08)	1.03(0.49,1.58)	0.91(0.16,1.66)	2.54(0.35,4.79)	3.61(1.69,5.56)	2.30(0.40,4.24)	0.48
	Respiratory	0.24(-0.47,0.96)	1.01(0.26,1.77)	1.37(0.22,2.53)	1.05(-2.05,4.24)	3.54(0.90,6.25)	3.48(0.55,6.50)	0.02

[a] Results from Poisson regression models, adjusted by time trend, temperature, RH, DOW, public holidays, influenza epidemics and annual total population. IQR in $PM_{2.5}$ was 29.1 μg/m^3, 24.9 μg/m^3.19.0 μg/m^3 for 2006-2009, 2010-2013 and 2014-2016, respectively; IQR in $PM_{10-2.5}$ was 13.9 μg/m^3, 11.6 μg/m^3.9.2 μg/m^3 for 2006-2009, 2010-2013 and 2014-2016, respectively; IQR in PM_{10} was 43.5 μg/m^3, 34.5 μg/m^3.25.2 μg/m^3 for 2006-2009, 2010-2013 and 2014-2016, respectively;

[b] linear interaction effect between ambient PM and time periods.

Table 5 Excess risk % (95% CI)[a] of mortality associated with 10 $\mu g/m^3$ increases in $PM_{2.5}$, $PM_{10-2.5}$ and PM_{10} (lag06) in Guangzhou, China, 2006-2016. Results from one and two pollutant models

Pollutant	Excess risk %(95%CI)		
	Total(non-accidental)	Cardiovascular	Respiratory
$PM_{2.5}$			
None	0.55(0.24,0.86)	1.15(0.68,1.62)	0.78(0.10,1.46)
Adjusted for NO_2	0.59(0.26,0.91)	1.25(0.76,1.74)	0.72(0.01,1.43)
Adjusted for SO_2	0.56(0.24,0.87)	1.19(0.71,1.67)	0.71(0.01,1.40)
$PM_{10-2.5}$			
None	0.99(0.48,1.50)	1.64(0.86,2.43)	0.75(-0.35,1.85)
Adjusted for NO_2	1.00(0.47,1.53)	1.78(0.97,2.59)	0.53(-0.60,1.68)
Adjusted for SO_2	0.96(0.44,1.48)	1.67 (0.88,2.47)	0.58(-0.53,1.71)
PM_{10}			
None	0.44(0.22,0.65)	0.82(0.49,1.14)	0.56(0.09,1.03)
Adjusted for NO_2	0.47(0.24,0.69)	0.91(0.57,1.26)	0.50(0.01,0.99)
Adjusted for SO_2	0.44(0.22,0.66)	0.85(0.52,1.19)	0.50(0.02,0.98)

[a]Results from Poisson regression models, adjusted by time trend, temperature, RH, DOW, public holidays, influenza epidemics and annual total population.

我国典型地区空气质量改善的健康效益评估及人群健康防护策略研究课题组

课题组负责人 黄薇

美国哈佛大学公共卫生学院环境卫生学博士（2003 年）
北京大学公共卫生学院劳动卫生与环境卫生学系教授、博士生导师
北京大学环境医学研究所副所长

主要研究方向为环境流行病学，包括空气污染的心肺系统健康损伤机制、风险评估、干预及政策制订等。自 2012 年起，担任世界卫生组织（WHO）环境健康顾问、专家组成员和课题负责人，参加和承担多项全球空气污染政策文件编纂和危害评估工作，主要包括空气污染致癌性评估、全球空气质量标准值更新、以及全球空气污染防护措施评估等。目前还担任 2021 年第 33 届国际环境流行病学会大会主席、国际环境期刊 Science of the Total Environment 副主编、Environmental Epidemiology 编委等职。此外，担任中国环境诱变剂学会青年委员会主任委员、国家室内空气质量标准修订工作组成员、国家环境基准工作委员会委员、欧美同学会留美医学委员会公共卫生专业委员会秘书长等职务。

此文章是国家自然科学基金 - 北京大学管理科学数据中心 2017 年资助课题“我国典型地区空气质量改善的健康效益评估及人群健康防护策略研究”的研究成果之一。该课题组负责人为北京大学公共卫生学院黄薇教授。该文章主要描述了广州市 2006-2016 年期间大气颗粒物（PM2.5，PM10-2.5，PM10）浓度水平变化特征，评估不同大气颗粒物对人群死亡的超额风险；并进一步探索研究期间颗粒物相关超额死亡估计值的时间变化趋势。研究结果表明广州市近年来大气颗粒物浓度水平虽呈下降趋势，但其相关的死亡风险仍可能存在。本研究的结果为今后继续加强环境空气污染控制措施，以保护公众健康提供了有力的理论依据。

2018 年 12 月发表于《Science of the Total Environment》

作者简介

POLICY REPORT SERIES

地　　址　北京市颐和园路5号北京大学理科5号楼4层
邮政编码　100871
联系电话　010-6276 7908
传　　真　010-6275 9641
网　　站　http://dcms.pku.edu.cn