



# Nonlinear relationships between air pollutant emissions and PM<sub>2.5</sub>-related health impacts in the Beijing–Tianjin–Hebei region

Bin Zhao<sup>a,b</sup>, Shuxiao Wang<sup>a,c,\*</sup>, Dian Ding<sup>a,c</sup>, Wenjing Wu<sup>a,c</sup>, Xing Chang<sup>a,c</sup>, Jiandong Wang<sup>d</sup>, Jia Xing<sup>a,c</sup>, Carey Jang<sup>e</sup>, Joshua S. Fu<sup>f</sup>, Yun Zhu<sup>g</sup>, Mei Zheng<sup>h</sup>, Yu Gu<sup>b,i</sup>

<sup>a</sup> School of Environment, and State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China

<sup>b</sup> Joint Institute for Regional Earth System Science and Engineering and Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095, USA

<sup>c</sup> State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China

<sup>d</sup> Multiphase Chemistry Department, Max Planck Institute for Chemistry, Mainz 55128, Germany

<sup>e</sup> U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, USA

<sup>f</sup> Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN 37996, United States

<sup>g</sup> School of Environmental Science and Engineering, South China University of Technology, Guangzhou 510006, China

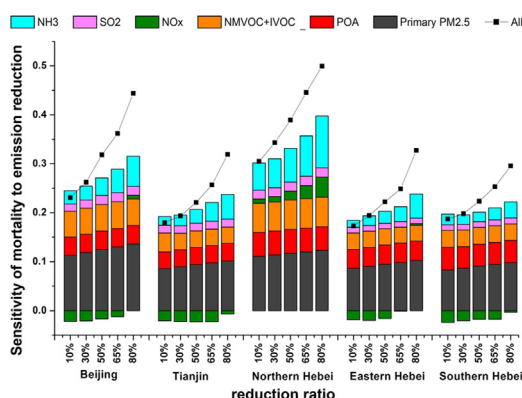
<sup>h</sup> SKL-ESPC and BIC-ESAT, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China

<sup>i</sup> University of California, Los Angeles Institute for Technology Advancement, Suzhou Industrial Park (UCLA ITA – SIP), Suzhou, China

## HIGHLIGHTS

- PM<sub>2.5</sub>-related mortality is most sensitive to the emissions of primary PM<sub>2.5</sub>.
- The mortality responds linearly to emission reduction of NMVOC, IVOC and SO<sub>2</sub>.
- The mortality is more sensitive to primary PM<sub>2.5</sub>, NH<sub>3</sub> and NO<sub>x</sub> at larger reductions.
- Multi-pollutant and multi-region controls result in larger marginal health benefit.
- A nationwide control strategy of NO<sub>x</sub> emissions is needed to enhance health benefit.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

### Article history:

Received 16 November 2018

Received in revised form 10 January 2019

Accepted 14 January 2019

Available online 16 January 2019

Editor: Jianmin Chen

### Keywords:

PM<sub>2.5</sub>

premature mortality

CMAQ/2D-VBS

## ABSTRACT

A direct and quantitative linkage of air pollution-related health effects to emissions from different sources is critically important for decision-making. While a number of studies have attributed the PM<sub>2.5</sub>-related health impacts to emission sources, they have seldom examined the complicated nonlinear relationships between them. Here we investigate the nonlinear relationships between PM<sub>2.5</sub>-related premature mortality in the Beijing–Tianjin–Hebei (BTH) region, one of the most polluted regions in the world, and emissions of different pollutants from multiple sectors and regions, through a combination of chemical transport model (CTM), extended response surface model (ERSM), and concentration-response functions (CRFs). The mortalities due to both long-term and short-term exposures to PM<sub>2.5</sub> are most sensitive to the emission reductions of primary PM<sub>2.5</sub>, followed by NH<sub>3</sub>, nonmethane volatile organic compounds and intermediate volatility organic compounds (NMVOC + IVOC). The sensitivities of long-term mortality to emissions of primary organic aerosol (POA), NMVOC + IVOC and SO<sub>2</sub> do not change much with reduction ratio, whereas the sensitivities to primary inorganic PM<sub>2.5</sub> (defined as all chemical components of primary PM<sub>2.5</sub> other than POA), NH<sub>3</sub> and NO<sub>x</sub> increase significantly

\* Corresponding author at: School of Environment, and State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China.  
E-mail address: [shxwang@tsinghua.edu.cn](mailto:shxwang@tsinghua.edu.cn) (S. Wang).

China  
extended response surface model (ERSM)

with the increase of reduction ratio. The emissions of primary PM<sub>2.5</sub>, especially those from the residential and commercial sectors, contribute a larger fraction of mortality in winter (57–70%) than in other seasons (28–42%). When emissions of multiple pollutants or those from both local and regional emissions are controlled simultaneously, the overall sensitivity of long-term mortality is much larger than the arithmetic sum of the sensitivities to emissions of individual pollutants or from individual regions. This implies that a multi-pollutant, multi-sector and regional joint control strategy should be implemented to maximize the marginal health benefits. For NO<sub>x</sub> emissions, we suggest a nationwide control strategy which significantly enhances the effectiveness for reducing mortality by avoiding possible side effects when only the emissions within the BTH region are reduced.

© 2019 Elsevier B.V. All rights reserved.

## 1. Introduction

Atmospheric fine particle (PM<sub>2.5</sub>) pollution has adverse effects on human health (Shang et al., 2013; Lelieveld et al., 2015). The effects are especially important in the Beijing-Hebei-Tianjin (BTH) urban agglomeration region, one of the most heavily polluted regions in China (Wang et al., 2017; Cai et al., 2017). It's estimated that monetize health losses caused by PM<sub>2.5</sub> pollution in the BTH region can reach 134.3 billion RMB, which accounts for 2.16% of the GDP in this region (Lv and Li, 2016). Protecting public health is the ultimate goal of air pollution control. Therefore, it is crucially important for environmental decision making to quantitatively link the PM<sub>2.5</sub>-related health impacts to air pollutant emissions from different sources.

PM<sub>2.5</sub> pollution is formed through complex physical and chemical processes. As a result, the relationships between PM<sub>2.5</sub> concentrations and emissions of precursors are nonlinear, and the nonlinearity is especially significant in urban agglomerations (Zhao et al., 2015; Zhao et al., 2017; Xing et al., 2017; Fu et al., 2012). In addition, some studies (Martenies et al., 2015; Burnett et al., 2014; Burnett et al., 2018) pointed out that the relationships between PM<sub>2.5</sub> concentrations and the resulting health effects are also nonlinear. When these two relationships are overlaid, we can expect highly nonlinear relationships between the PM<sub>2.5</sub>-associated health effects and the emissions of precursors. A number of studies (GBD MAPS Working Group, 2016; Hu et al., 2017; Fann et al., 2012; Wang et al., 2015; Heo et al., 2016; Andersson et al., 2009) have attributed the PM<sub>2.5</sub>-associated health effects to different emission sources, but to our best knowledge, none of them have explicitly considered the aforementioned nonlinear relationships, which brings inaccuracy to the source attribution results. Therefore, it's a meaningful and also challenging scientific issue to quantify the nonlinear responses of PM<sub>2.5</sub>-related health effects to primary air pollutant emissions.

In this study, we quantitatively evaluate the nonlinear relationships between premature mortality caused by long-term/short-term exposures to PM<sub>2.5</sub> in the BTH region and emissions of different air pollutants from multiple sectors and regions, by combining a chemical transport model (CTM), concentration-response functions (CRFs), and an extended response surface model (ERSM). By providing the first quantitative assessment of the nonlinear relationships between emission reductions and health impacts, this study helps decision makers in the BTH region to develop specific and optimized control measures that best protect the public health. Also, the modeling framework developed in this study enables an instantaneous prediction of PM<sub>2.5</sub>-related mortality for any given emission scenario. It can be readily adopted by researchers, policymakers, and advocates from public, private, and nonprofit sectors, and holds strong potential for replication in other regions in the world, further extending this study's reach and impact.

## 2. Methods

### 2.1. Health impact assessment methodology

In this study, we estimate the health effects due to both short-term and long-term exposures to ambient PM<sub>2.5</sub>. For long-term health impact

assessment, Burnett et al. (2014) proposed integrated expose-response (IER) function, which were constructed by combining risk estimates from studies of ambient and household air pollution, and active/second-hand smoking that cover a full range of PM<sub>2.5</sub> exposure up to about 30000 µg/m<sup>3</sup> (Cohen et al., 2017; Burnett et al., 2014). The IER function is given by Eq. (1), which has been proved to fit best to the actual risk estimates among a variety of equation forms (Cohen et al., 2017; Burnett et al., 2014).

$$\Delta Y_i = y_{0,i} P \times \frac{RR_i - 1}{RR_i} \quad (1)$$

$$RR_i = \begin{cases} 1, & C < C_0 \\ 1 + \alpha_i \left[ 1 - e^{-\gamma_i (C - C_0)^{\delta_i}} \right], & C \geq C_0 \end{cases}$$

where  $\Delta Y_i$  refers to PM<sub>2.5</sub>-induced mortality from endpoint  $i$ ;  $y_{0,i}$  refers to the actual mortality rate of endpoint  $i$  at the current PM<sub>2.5</sub> concentration ( $C$ );  $P$  refers to exposed population;  $C_0$  refers to threshold PM<sub>2.5</sub> concentration below which no health impact is expected.  $\alpha_i$ ,  $\gamma_i$ , and  $\delta_i$  are regression parameters for endpoint  $i$ . According to the IER function, the change in mortality due to a unit concentration change decreases significantly with the deterioration of PM<sub>2.5</sub> pollution. Recently, Burnett et al. (2018) developed new CRFs for long-term PM<sub>2.5</sub> exposures based on only cohort studies of ambient air pollution, which resulted in larger mortality estimates. However, this would not change our major conclusions about the nonlinear emission-mortality relationships, since the general shape of the functions retained. In this study, we adopt the same health endpoints and IER parameters ( $\alpha_i$ ,  $\gamma_i$ , and  $\delta_i$ ) as in Burnett et al. (2014). These endpoints include chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), lung cancer, and stroke for adults > 25 years old, as well as acute lower respiratory infection (ALRI) for children < 5 years old. The disease specific baseline mortality rates by age and gender are obtained from the Institute of Health Metrics and Evaluation (Global Burden of Disease Collaborative Network, 2017).

For health impact assessment of short-term exposure to PM<sub>2.5</sub>, the CRFs are developed by epidemiological studies based on time series analysis of PM<sub>2.5</sub> and health. In most studies (Shang et al., 2013; Wang et al., 2015; Dominici et al., 2002; Kan and Chen, 2004), the incidence of mortality caused by air pollution is considered to be subject to Poisson distribution. Subsequently, the relationship between mortality and PM<sub>2.5</sub> concentrations can be regressed in the following form by using Poisson regression (log-linear regression) or similar methods (Kan et al., 2008; Dominici et al., 2002; Shang et al., 2013; Kan and Chen, 2004).

$$\Delta Y_i = y_{0,i} P \left[ 1 - e^{\beta_i (C - C_0)} \right] \quad (2)$$

where  $\Delta Y_i$ ,  $y_{0,i}$ ,  $P$ ,  $C$ , and  $C_0$  have the same meaning as defined in Eq. (1).  $\beta_i$  is a regression coefficient derived from epidemiological studies, which refers to excess risk of mortality per each increase in 1 µg/m<sup>3</sup> of PM<sub>2.5</sub> concentration. Reasonable regression results have been obtained using Eq. (2) in over 25 epidemiological studies conducted in China (Shang et al., 2013), where the PM<sub>2.5</sub> concentrations range from very small to very large (mean concentration > 170 µg/m<sup>3</sup>), indicating the

applicability of Eq. (2) to the Chinese environments. Based on Eq. (2), the relationship between  $\Delta Y_i$  and  $C$  presents a slightly convex function form, indicating subtly less marginal effect at larger concentration increase. The health endpoints considered in the short-term assessment include all-cause mortality, cardiovascular mortality, and respiratory mortality. The baseline mortality rates are derived from China Health and Family Planning Statistics Yearbook 2015 (National Health and Family Planning Commission of China, 2015) and Huang and Zhang (2013), and the parameter estimates are taken from Chen et al. (2011), a local study over the BTH region. It should be noted that, in addition to mortality, the short-term  $PM_{2.5}$  exposure also leads to various types of morbidity (e.g., cardiovascular and respiratory hospital admissions or outpatients). We focus on mortality in the present study since it accounts about 80% of the total monetized health losses (Kan and Chen, 2004; Wu, 2016).

The age-specific population data at city level in 2014 are acquired from the statistical bureaus of Beijing, Tianjin and Hebei, and the spatial distribution of population at sub-city level is based on the LandScan dataset at  $30'' \times 30''$  (approximately  $1 \text{ km} \times 1 \text{ km}$ ) resolution (Oak Ridge National Laboratory, 2016). The spatial distribution of population is shown in Fig. S1. Annually average and monthly average  $PM_{2.5}$  concentrations derived in Section 2.2 are fed into the CRFs to assess the health impacts due to long-term and short-term  $PM_{2.5}$  exposures, respectively. To give the uncertainty of the health effects, we calculate the 95% confidence intervals (CIs) using 95% CIs of the parameters of the CRFs for both short-term and long-term assessments.

## 2.2. Determination of exposed concentrations

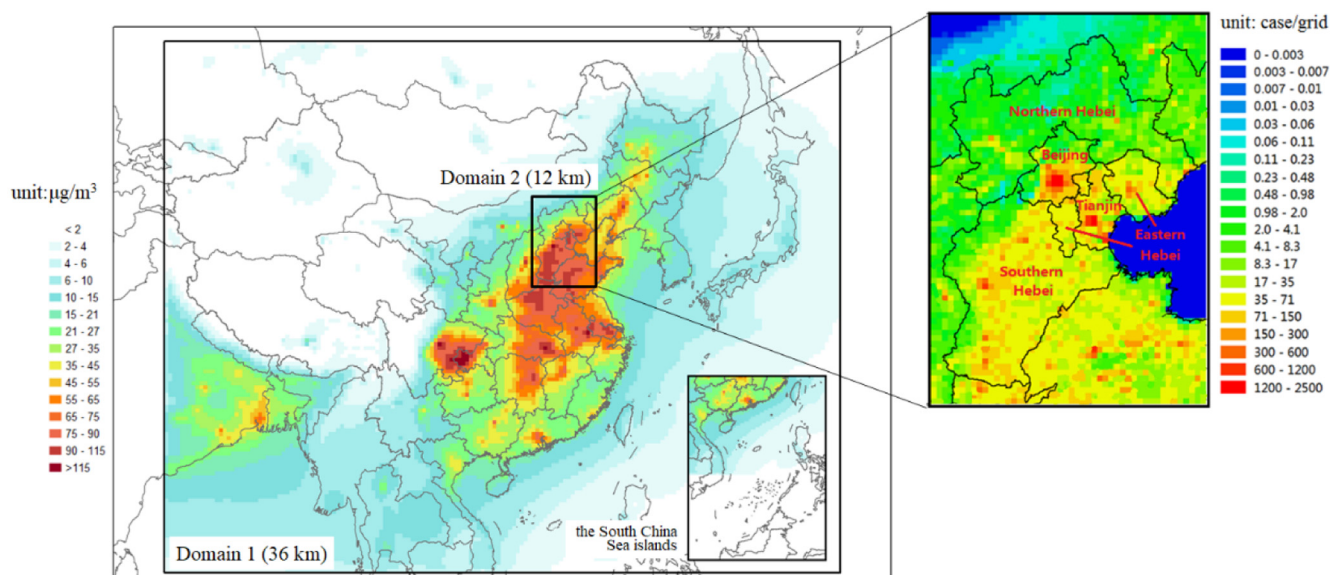
The exposed concentrations of  $PM_{2.5}$  ( $C$  in Eqs. (1) and (2)) in the base case are simulated using the Community Multi-scale Air Quality model with two-dimensional Volatility Basis Set extension (CMAQ/2D-VBS; Zhao et al., 2016). The CMAQ/2D-VBS model was developed by incorporating the 2D-VBS framework in CMAQ, a widely used three-dimensional CTM, in order to improve the simulation of secondary organic aerosol (SOA) (Zhao et al., 2016). The Weather Research and Forecasting (WRF) model version 3.7 is used to simulate the meteorological field to provide input data for the CMAQ/2D-VBS model. The simulation periods are January, March, July and October in 2014, representing four seasons. We select these four months in 2014 because they agree best with the average meteorological conditions in winter,

spring, summer, and fall during 2004–2014, ensuring the representativeness of meteorological conditions in the simulation periods (Zhao et al., 2017).

We apply the WRF/CMAQ/2D-VBS model to double-nesting simulation domains, with grid resolutions of  $36 \text{ km} \times 36 \text{ km}$  and  $12 \text{ km} \times 12 \text{ km}$ . The first domain covers China mainland and its surrounding areas, and the second domain covers the BTH region, as shown in Fig. 1. The configurations of WRF and CMAQ/2D-VBS and the emission inventory used in this paper are the same as Zhao et al. (2017). In brief, in the BTH region, we use a high-resolution anthropogenic emission inventory in 2014 developed by Zheng et al. (2018). The anthropogenic emission inventory in other provinces of China was developed in our previous studies (Wang et al., 2014; Zhao et al., 2018b). The emissions from open burning of agricultural residue have been included in both inventories. The emissions outside China are obtained from the MIX emission inventory (Li et al., 2015) for 2010, which is the latest year available. The biogenic emissions are calculated by the Model of Emissions of Gases and Aerosols from Nature (MEGAN; Guenther et al., 2006). The simulated results from WRFv3.7 and CMAQ/2D-VBS model generally agree well with ground observations (Zhao et al., 2017).

The 3-D CTM is time-consuming and computationally expensive. In this study, we acquire the exposed  $PM_{2.5}$  concentrations in various emission control scenarios using the ERSM technique (Zhao et al., 2015), which enables quick prediction of  $PM_{2.5}$  concentrations in any given emission scenario. The conventional response surface model (RSM) builds the relationships between  $PM_{2.5}$  concentrations and a set of control variables (i.e., emissions of specific precursors from specific sources) using a number of CTM simulation scenarios and advanced statistical techniques (Xing et al., 2011; Wang et al., 2011). The ERSM technique extends the applicability of conventional RSM to a much larger number of control variables and geographical regions (Zhao et al., 2015). It first quantifies the relationship between  $PM_{2.5}$  concentrations and precursor emissions in each single region using the conventional RSM, and then assesses the effects of inter-regional transport of  $PM_{2.5}$  and its precursors on  $PM_{2.5}$  concentration in the target region. The ERSM technique has showed good performances in several recent studies (Zhao et al., 2015; Zhao et al., 2017; Xing et al., 2017).

The establishment and validation of ERSM in the BTH region have been described in Zhao et al. (2017), so we only summarize several key points. First, we defined 5 target regions in the BTH region,



**Fig. 1.** The simulation domains in this study and simulated annual  $PM_{2.5}$  concentrations (left), as well as the spatial distribution of premature mortality by stroke due to long-term exposure to  $PM_{2.5}$  pollution in the BTH region (right).



i.e., Beijing, Tianjin, Northern Hebei, Eastern Hebei, and Southern Hebei (see Fig. 1). Next, we used 1121 scenarios simulated by CMAQ/2D-VBS to establish the ERSR prediction system, which maps atmospheric PM<sub>2.5</sub> concentrations versus emissions of 55 combinations of regions, sectors, and pollutants. We assessed the prediction capability of the ERSR prediction system by employing the “out-of-sample” and 2D-isopleths validation methods, and showed satisfying accuracy and stability.

### 2.3. Sensitivity of mortality to emission reductions

We calculate the sensitivity of mortality to emission reductions of various sources with the following formula:

$$S_{i,j} = \frac{(H_{i,j} - H_{i,0})/H_{i,0}}{R_j - 1}, (0 \leq R_j \leq 1) \quad (3)$$

where  $S_{i,j}$  refers to the sensitivity of health endpoint  $i$  to emission source  $j$ ;  $R_j$  refers to the ratio of emissions from source  $j$  to the base-case emissions;  $H_{i,j}$  is the health effect of endpoint  $i$  when the emission ratio of source  $j$  is  $R_j$ , which is calculated using the ERSR prediction system developed above;  $H_{i,0}$  refers to the health effect in the base case. For each emission source, we calculate  $S_{i,j}$  for reduction ratios ( $1 - R_j$ ) of 10%, 30%, 50%, 65%, 80% to assess the nonlinear relationships between health effects and emission reductions.

There are also other methods to attribute PM<sub>2.5</sub>-related mortality to different emission sources. Global Road Safety Facility et al. (2014) summarized three methods: 1) direct proportion of burden, 2) top of curve, and 3) average risk. This study aims to calculate the changes in mortality in response to emission reductions from various sources. We used Method 2 (top of curve), because this is the only method that mimics how the mortality would actually change if the emissions from certain sources were to be reduced. Global Road Safety Facility et al. (2014) also suggested that “Method 2 is the most appropriate when one is predicting the future change in risk if certain emissions sources were eliminated”. Method 1 (direct proportion of burden) or Method 3 (average risk) both introduced certain assumptions so that the health burdens attributed to individual emission sources are independent of the sequence in which they are removed. These two methods are suitable to attribute the current health burden to different sources, but are not applicable to the prediction of change in mortality when emissions are controlled. If Method 1 or Method 3 were applied in this study, the sensitivities of mortality to emission reduction would be quite similar to those of PM<sub>2.5</sub> concentrations presented in Zhao et al. (2017).

## 3. Results and discussion

### 3.1. PM<sub>2.5</sub>-related premature mortality in the BTH region

The premature mortalities by different diseases due to long-term PM<sub>2.5</sub> exposure in the BTH region are shown in Fig. 2a. According to our assessment, 17.42 (95% CI, 9.45–24.40) thousand, 36.29 (27.24–48.48) thousand, 13.53 (5.19–18.19) thousand, 61.91 (27.71–79.93) thousand, and 0.91 (0.62–1.14) thousand people die of COPD, IHD, lung cancer, stroke, and ALRI due to long-term exposure to PM<sub>2.5</sub> in the BTH region annually. Stroke is the most important health endpoint, accounting for 48% of the total premature deaths due to long-term exposure. Beijing, Tianjin, and cities in Southern Hebei are areas where people most severely suffer from PM<sub>2.5</sub>-related mortality, and cities in Northern Hebei have the least mortality.

The short-term exposure to PM<sub>2.5</sub> raises more concerns when heavy pollution episode occurs. As Fig. 2b shows, 18.72 (11.20–25.65) thousand premature mortality is caused by the short-term exposure to PM<sub>2.5</sub> in the BTH region annually, among which 59% and 16% are by cardiovascular and respiratory diseases, respectively. Similar to long-term

effects, the majority of short-term health effects come from Beijing, Tianjin, and cities in Southern Hebei.

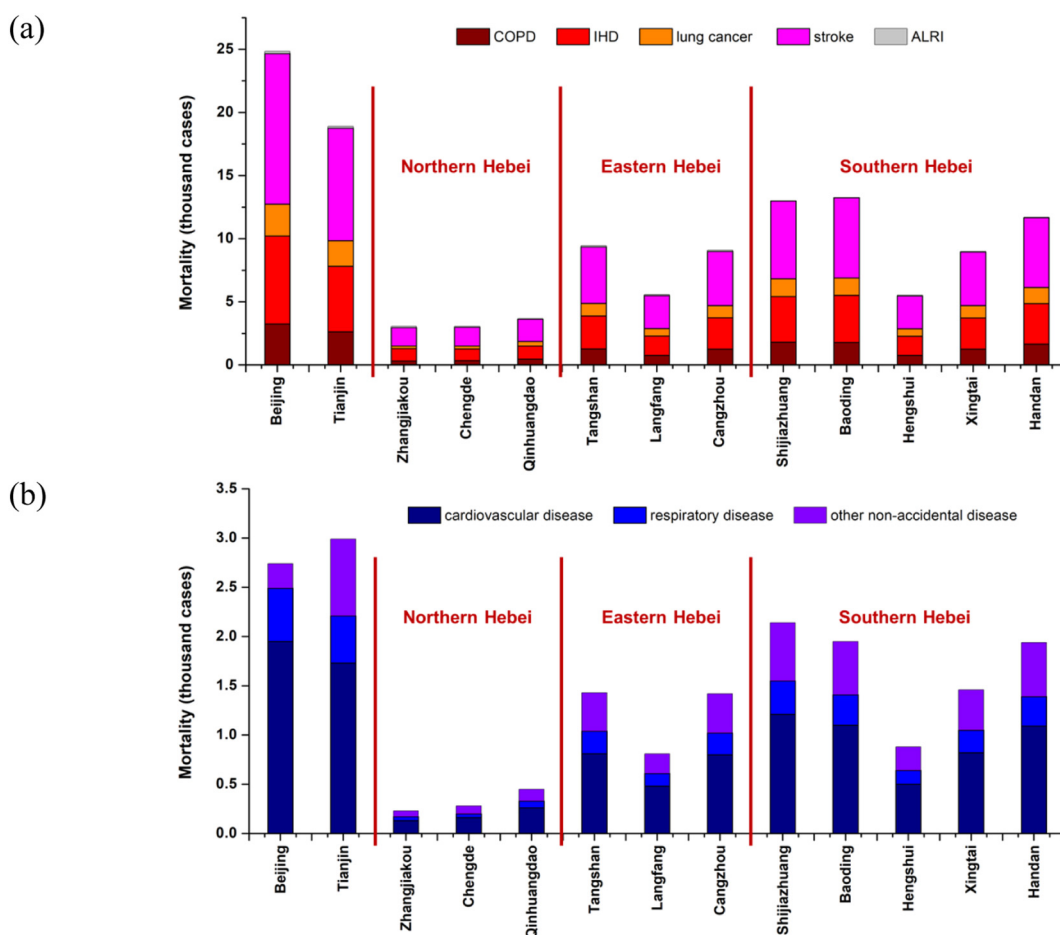
We also assess the spatial distribution of health effects due to PM<sub>2.5</sub> pollution, and the long-term mortality by stroke is shown in Fig. 1. The spatial distribution characteristics of other health endpoints due to either long-term or short-term PM<sub>2.5</sub> exposures are highly similar (Fig. S2). Comparing the spatial distribution of the health effects with population and PM<sub>2.5</sub> concentrations (Fig. S1), we can conclude that the health effects are strongly correlated with population intensity. For this reason, high mortality appears in urban areas.

### 3.2. Nonlinear relationships between air pollutant emissions and mortality

We assess the nonlinearity between air pollutant emission control and PM<sub>2.5</sub>-related mortality using the ERSR technique and the sensitivity analysis method described in Sections 2.1 and 2.2. For long-term exposure, to simplify the analysis, we sum up the premature mortality by COPD, IHD, lung cancer, stroke, and ALRI to approximately represent the total PM<sub>2.5</sub>-related mortality, following previous studies (Cohen et al., 2017; Apte et al., 2015). As shown in Fig. 3, among all pollutants, the annual mortality due to long-term exposure to PM<sub>2.5</sub> is most sensitive to emissions of primary inorganic PM<sub>2.5</sub>, which is defined as all chemical components of primary PM<sub>2.5</sub> other than organics, including black carbon, metals, crustal elements, etc. Primary organic aerosol (POA) is treated separately because it experiences chemical oxidations and forms SOA in the CMAQ/2D-VBS model, whereas primary inorganic PM<sub>2.5</sub> is assumed to be chemically inert. It's worth noting that the estimation methods of the mortality assume that the health effects depend only on the inhaled amount of PM<sub>2.5</sub> and are independent of the chemical composition, which appears reasonable in view of the available quantitative epidemiological studies. However, some studies have reported that some aerosol species, such as the carbonaceous aerosols (black carbon and organic aerosols), could be significantly more toxic than others (Tuomisto et al., 2008; Lelieveld et al., 2015). The relative toxicity of different aerosol species may affect the relative contributions of primary inorganic PM<sub>2.5</sub> emissions to premature mortality, which warrants further in-depth study.

Among all sources of primary inorganic PM<sub>2.5</sub>, the industry sector is estimated to make the largest contribution (45–70%), followed by the residential and commercial sectors (20–45%), while the contributions from power plants and transportation are quite small (<15%). The sensitivity of long-term mortality to primary inorganic PM<sub>2.5</sub> emissions increases gradually by ~20% when the emission reduction ratio increases from 10% to 80%. In contrast, the sensitivity of PM<sub>2.5</sub> concentrations remains constant regardless of reduction ratio according to our previous study (Zhao et al., 2017). The difference is explained by the fact that the mortality reduction due to a unit drop of PM<sub>2.5</sub> concentration is larger at lower PM<sub>2.5</sub> concentration range, according to the curvilinear shape of the IER function. For this reason, emission of primary inorganic PM<sub>2.5</sub> is expected to be controlled as stringent as possible in the long run to efficiently prevent PM<sub>2.5</sub>-related mortality.

Among the precursors, the long-term mortality is primarily sensitive to the emissions of NH<sub>3</sub>, nonmethane volatile organic compounds and intermediate volatility organic compounds (NMVOC+IVOC), and POA. Their relative importance differs by region and reduction ratio (Fig. 3). The large contributions of NMVOC and IVOC are different from the results in many modeling studies (Wang et al., 2015; Wang et al., 2011), primarily because of an improved treatment of SOA formation from these precursors in the CMAQ/2D-VBS. In the present study, we have combined NMVOC and IVOC emissions into an individual control variable. Nevertheless, the O<sub>3</sub> and PM<sub>2.5</sub> formation potentials of NMVOC and IVOC are quite different (Zhao et al., 2016; Wu et al., 2017). In addition, different control strategies are required to control NMVOC and IVOC since the control technologies designed for NMVOC may not effectively reduce IVOC emissions (Gordon et al., 2014; Jathar et al., 2014). Considering the important contributions of NMVOC and IVOC, further



**Fig. 2.** Annual premature mortality due to long-term (a) and short-term (b) exposures to PM<sub>2.5</sub> concentrations in the BTH region. Only median values of the mortality estimates are displayed in this figure.

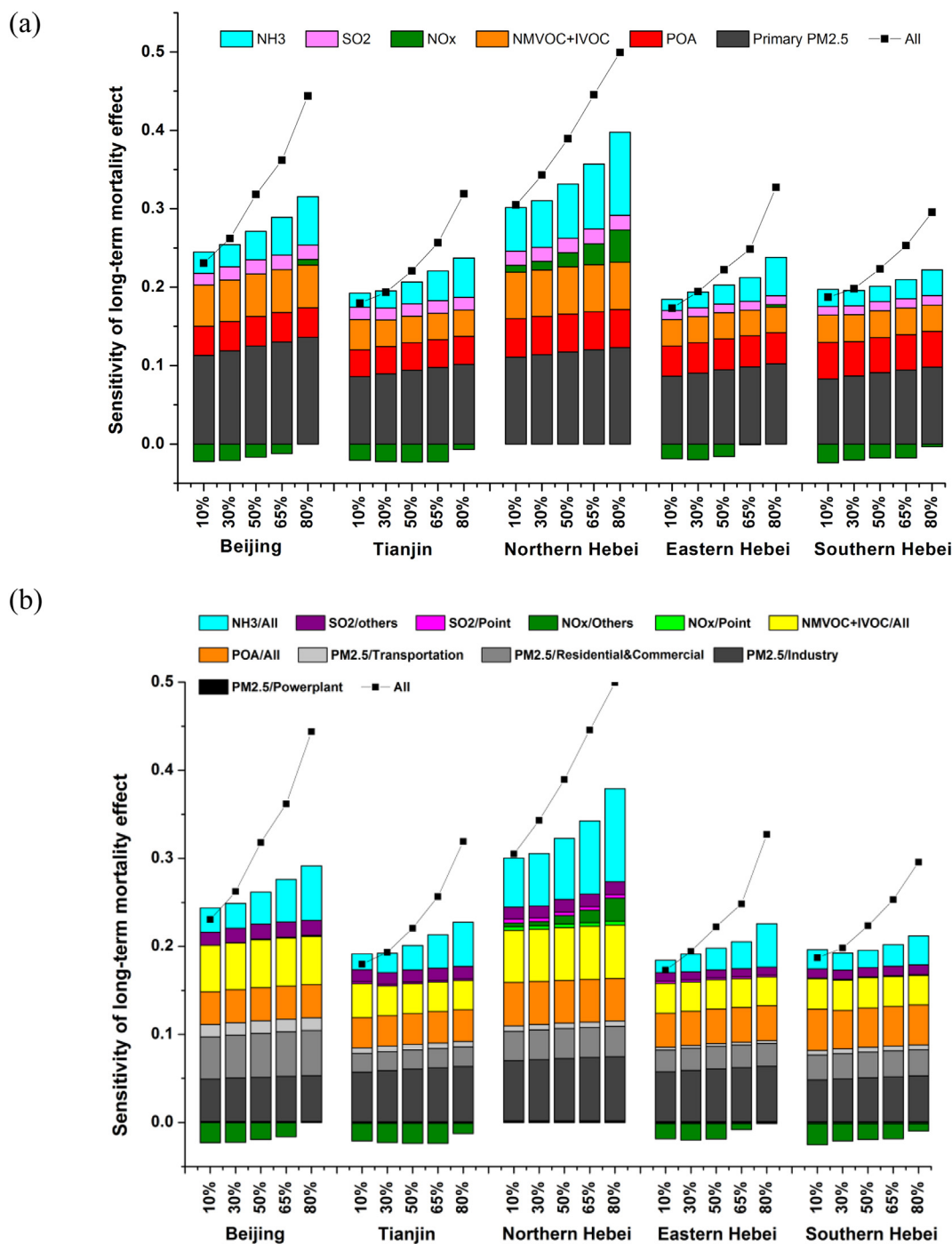
study is needed to separately assess the effects of NMVOC and IVOC emissions from various sectors on premature mortality.

The sensitivities of mortality to emission reductions of POA and NMVOC+IVOC roughly remain unchanged at various reduction ratios, and the sensitivities to SO<sub>2</sub> increase marginally with increasing emission reduction. This is a combined effect of the emission-concentration relationships and the CRFs. First, the sensitivities of PM<sub>2.5</sub> to emission reductions of NMVOC+IVOC and POA decrease slightly with increasing reduction ratio, and the sensitivities to SO<sub>2</sub> roughly remain invariant, according to Zhao et al. (2017). Second, due to the curvilinear IER function, the sensitivities of mortality to PM<sub>2.5</sub> concentration increase with decreasing PM<sub>2.5</sub> concentration. In contrast, the sensitivities to NH<sub>3</sub> emissions increase substantially with the increase of reduction ratio because of 1) an increased sensitivity of PM<sub>2.5</sub> concentrations due to a transition from NH<sub>3</sub>-rich to NH<sub>3</sub>-poor conditions (Wang et al., 2011) and 2) an increased marginal mortality benefit at larger reductions. The sensitivities of mortality to NO<sub>x</sub> emissions can be either negative or positive, depending on region and reduction ratio – they tend to be negative at small reduction ratio and positive at large reductions, since a small reduction in NO<sub>x</sub> emissions is likely to produce more oxidants due to a NMVOC-limited photochemical regime, thus leading to the formation of more secondary inorganic and organic aerosols (Dong et al., 2014; Zhao et al., 2015; Cai et al., 2017). However, the results would be quite different if the NO<sub>x</sub> emissions outside the BTH region are jointly controlled. We design a number of sensitivity scenarios in which the NO<sub>x</sub> emissions in the whole China are uniformly reduced by 10%–80% (depending on scenario), and re-run the CMAQ/2D-VBS model for two nested domains. The difference between the baseline and sensitivity simulations represents the influence of NO<sub>x</sub> emission reductions in the

whole China. As shown in Fig. 4, the sensitivities of mortality in the BTH to uniform NO<sub>x</sub> reduction in China are positive even at a small reduction ratio. The reason is that NO<sub>x</sub> emission reductions in farther regions are more likely to lead to a net decrease in PM<sub>2.5</sub> concentration than local emission reductions, since the photochemical regime usually changes from NMVOC-limited in local urban areas at ground level to NO<sub>x</sub>-limited in downwind regions or higher altitudes where regional transport occurs (Xing et al., 2011). Therefore, it is critically important to enforce stringent NO<sub>x</sub> emission controls on national scale.

Regarding different emission sectors, the contributions of SO<sub>2</sub> and NO<sub>x</sub> emissions are dominated by non-point sources (Fig. 3b). If all pollutants and sectors are jointly controlled, the overall sensitivity of long-term mortality dramatically increases with reduction ratio, and this sensitivity is remarkably larger than the sum of the sensitivities to emissions of individual pollutants and sectors, mainly because of the curvilinear shape of the IER functions. This is in contrast to the sensitivities of PM<sub>2.5</sub> concentrations shown in Zhao et al. (2017), where the overall sensitivity is generally similar to the sum of the sensitivities to individual pollutants/sectors. The nonlinearity indicates that extra health benefits will be achieved if a multi-pollutant multi-sector joint control strategy is implemented.

As for short-term exposure, we assess the sensitivities of all-cause mortality to the emissions of various pollutants from various sectors (Fig. 5). The relative contributions of different pollutants and sectors are largely similar to those of long-term exposure. However, the patterns of the nonlinear relationships are quite different. Specifically, when the emission reduction ratio increases from 10% to 80%, the sensitivity of mortality to primary inorganic PM<sub>2.5</sub> emissions increases so slightly that it seems to be constant. This can be explained by the fact

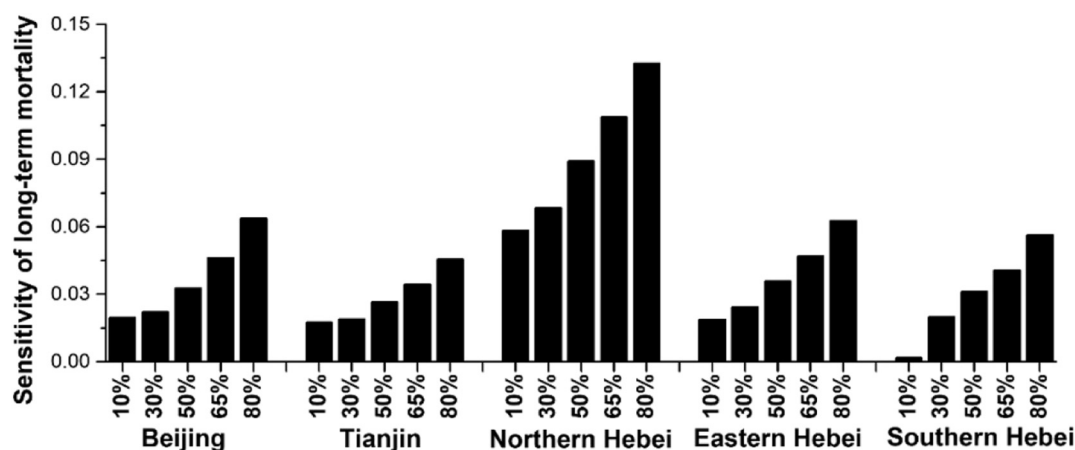


**Fig. 3.** Sensitivity of annual mortality due to long-term exposure to  $\text{PM}_{2.5}$  to stepped control of each pollutant (a) and each pollutant-sector combination (b) within the BTH region. The X-axis represents the reduction ratio (i.e.,  $1 - \text{emission ratio}$ ). The Y-axis represents the sensitivity of mortality, as defined by Eq. (3). The colored bars denote the sensitivity of mortality when a specific emission source is controlled while the others remain the base-case level. The black dotted line is the sensitivity of mortality when all emission sources are jointly controlled.

that the nonlinearity of the CRFs for short-term assessment (Eq. (2)) is much weaker than that of the IER function (Eq. (1)). If all pollutants and sectors are jointly controlled, the sensitivity of mortality is similar to or less than the sum of the sensitivities to emissions of individual pollutants and sectors, and the sensitivity only increases slightly with reduction ratio. The finding implies that, to minimize the mortality in the long run, multi-pollutant multi-sector control strategies should be implemented, but this strategy may not be vital for temporary control measures of severe pollution events.

We further analyze the seasonal feature of sensitivity of short-term mortality to emissions of various pollutants and sectors. We choose

Beijing and Northern Hebei as examples, as shown in Fig. 5b. The sensitivities show significant variations among different seasons. The emissions of primary  $\text{PM}_{2.5}$  (including primary inorganic  $\text{PM}_{2.5}$  and POA) contribute a much larger fraction of mortality in winter (57–70%) than in other seasons (28–42%), mainly as a result of weaker vertical mixing and slower reactions of gaseous precursors (Zhao et al., 2018a; Wang et al., 2011). Among different sources of primary inorganic  $\text{PM}_{2.5}$ , the residential and commercial sector has relatively larger contribution in winter because 1) the use of coal and biomass for heating enlarges the residential emissions in winter, and 2) the weaker vertical mixing in winter favors the accumulation of emissions from low-level sources,



**Fig. 4.** Sensitivity of annual mortality due to long-term exposure to PM<sub>2.5</sub> in the BTH region to stepped control of NO<sub>x</sub> emissions across the whole China. The X-axis shows the reduction ratio (= 1 – emission ratio). The meanings of two axes are the same as in Fig. 3.

resulting in a relatively larger contribution from residential sources. The sensitivities of mortality to gaseous precursors are generally larger in summer than in winter primarily because of accelerated chemical reactions due to stronger radiation and higher temperature. The sensitivities to NO<sub>x</sub> are more complicated – they are mostly negative in winter and positive in summer, and change from negative at small reduction to positive at large reduction in spring and autumn, because the photochemistry is prone to be NMVOC-limited in winter and NO<sub>x</sub>-limited in summer (Zhao et al., 2013; Zhao et al., 2015; Xing et al., 2017). Therefore, a NO<sub>x</sub> emission control strategy that lays emphasis on summer could maximize the public health benefits. A potential strategy is to strengthen the on-site inspection of the operation of NO<sub>x</sub> control facilities in summer, especially the denitrification facilities in power plants and industrial sectors. This helps to ensure the normal operation of control equipment and minimize NO<sub>x</sub> emissions without permission in summer.

### 3.3. Nonlinear relationships between region-specific emission control and mortality

We examine the nonlinear relationships between region-specific emission control and health effects by using the same method applied in Section 3.2. Here we select long-term mortality in Beijing as an example, as shown in Fig. 6. The annual mortality in Beijing is most sensitive to local emissions among the five regions, but the relative contributions of local and non-local sources differ significantly by pollutants. For primary inorganic PM<sub>2.5</sub>, POA, and SO<sub>2</sub>, local emissions account for more than 60% of the total contributions from all regions. With respect to NH<sub>3</sub> and NMVOC+IVOC, local emissions account for about 50% and one third, respectively. The sensitivity of mortality to local primary inorganic PM<sub>2.5</sub> emissions increases by ~20% when the reduction ratio increases from 10% to 80%, while the sensitivity to local NH<sub>3</sub> emissions nearly doubles in response to such increase in the reduction ratio. For SO<sub>2</sub>, POA, and NMVOC+IVOC, no obvious change in sensitivities with the reduction ratio is noted. For NO<sub>x</sub>, the sensitivity to local emissions is negative, whereas the sensitivities to emissions from other regions, especially Southern Hebei from which a large amount of air pollutants are transported to Beijing (Chang et al., 2018), could change from negative to positive when the reduction ratio increases from 10% to 80%.

For each individual pollutant, when emissions from all regions except Beijing are controlled together, the overall sensitivity of mortality nearly equals the arithmetic sum of the sensitivities to each single region, indicating quasi-linear effects of emission control among region outside Beijing. Nevertheless, when emissions from all regions including Beijing are controlled together, the overall sensitivity of mortality exceeds the arithmetic sum of the sensitivities to emissions from each

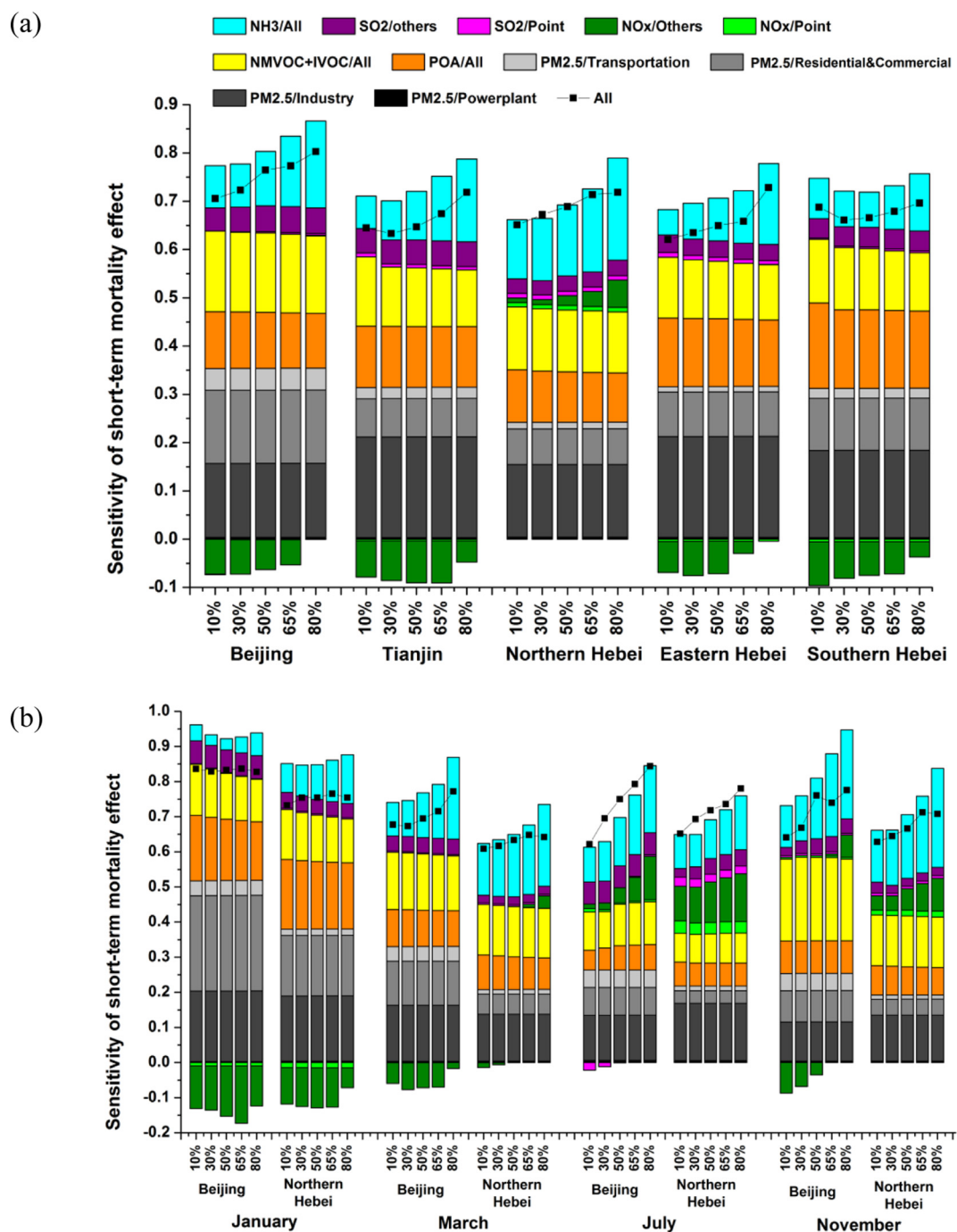
single region, and the differences are more pronounced when the reduction ratio is large and/or multiple pollutants are controlled simultaneously (see the rightmost columns in Fig. 6). The enhanced sensitivity of mortality, which is an integrated effect of the nonlinearity in both atmospheric chemical reactions and the IER functions, implies that additional health benefits will be achieved when multi-pollutant and regional joint control strategies are implemented. Although we use Beijing as an example in the preceding analysis, similar increment in sensitivity due to multi-region and multi-pollutant controls is also found for other regions in the BTH.

### 3.4. Comparison with previous studies

We compared our results with previous studies which attributed the PM<sub>2.5</sub>-associated health effects to different emission sources (GBD MAPS Working Group, 2016; Hu et al., 2017; Fann et al., 2012; Wang et al., 2015; Heo et al., 2016; Andersson et al., 2009). GBD MAPS Working Group (2016) and Hu et al. (2017) quantified the contributions of different economic sectors to mortality due to long-term PM<sub>2.5</sub> exposure in China. The two studies both showed that industrial and domestic sectors were the most important emission sources for PM<sub>2.5</sub>-related mortality in the BTH region, which agrees with the results of this study. Nevertheless, this study also assessed the relationships between PM<sub>2.5</sub>-associated mortality in the BTH and emissions of different pollutants from different regions and characterized the nonlinearity of the relationships, which was not investigated in GBD MAPS Working Group (2016) and Hu et al. (2017).

Since limited studies have apportioned the sources of mortality in the BTH region, we also compare with a number of studies for other polluted regions in the world. Wang et al. (2015) evaluated the source contributions of mortality due to short-term PM<sub>2.5</sub> exposure in the Yangtze River Delta (YRD) region of China. They also found that industrial and domestic sectors were two largest emission sources for PM<sub>2.5</sub>-associated mortality, consistent with the results of this study for the BTH region. Besides, Wang et al. (2015) found that the PM<sub>2.5</sub>-related mortality in YRD was most sensitive to emissions of primary PM<sub>2.5</sub>, followed by NH<sub>3</sub>, in agreement with our results for the BTH. However, Wang et al. (2015) reported a negligibly small contribution from NMVOC, while our study reveals that the contributions from NMVOC and IVOC are comparable to those from other gaseous precursors, probably because the CMAQ/2D-VBS model applied in our study significantly improved the simulation of SOA formation. Regarding regional contributions, Wang et al. (2015) showed that the mortality in a specific region was most sensitive to local emissions among all regions within the YRD, which is similar to our finding for Beijing.





**Fig. 5.** Sensitivity of annual (a) and monthly (b) short-term  $PM_{2.5}$ -related mortality to stepped control of each pollutant-sector combination within the BTH region. The meanings of two axes, black dotted lines, and colored bars are the same as in Fig. 3.

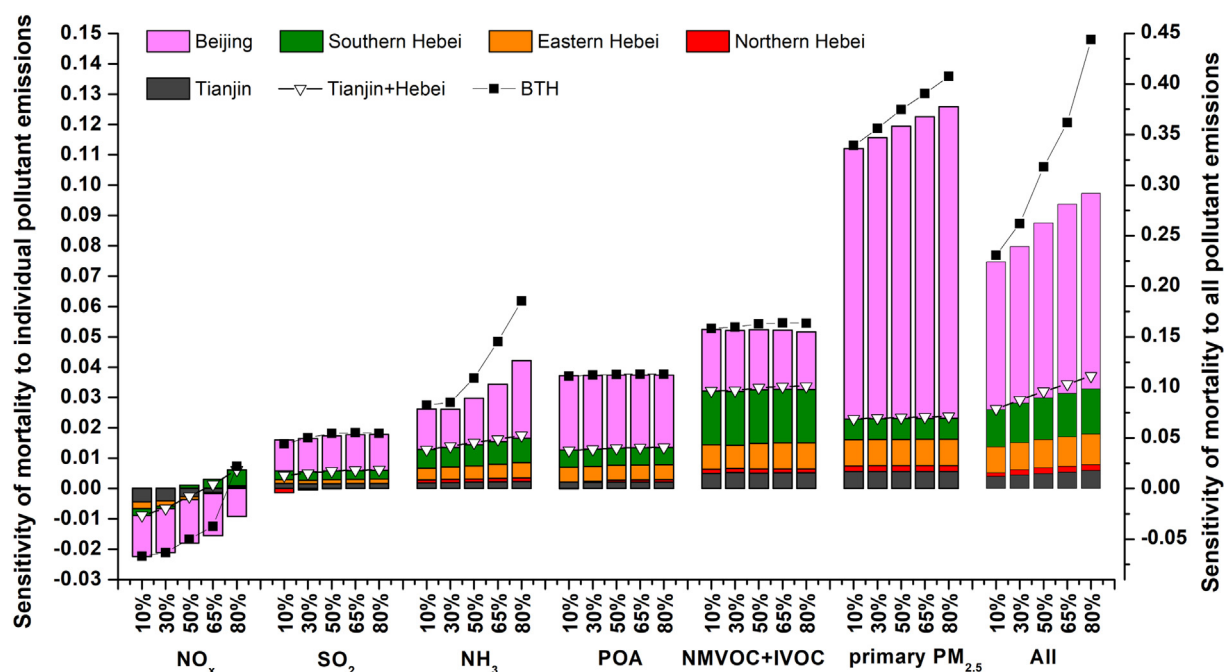
Fann et al. (2012) and Heo et al. (2016) estimated the sensitivity of long-term  $PM_{2.5}$ -related mortality in the United States to emission reductions. They found that the mortality was most sensitive to emissions of primary  $PM_{2.5}$ , followed by  $SO_2$  and  $NO_x$ , and  $NH_3$ . This is partially different from our results that the mortality is more sensitive to  $NH_3$  than to  $SO_2$  and  $NO_x$ , which can be explained by the differences in emission inventory and photochemical regimes between United States and the BTH region. Heo et al. (2016) further reported a 7% increase in marginal health benefits of  $SO_2$  control and a 26% increase for  $NO_x$  from 2005 to 2016 (differences in population and income level between two years have been adjusted), because of significantly reduced  $SO_2$  and  $NO_x$  emissions during this period. This is consistent with our finding that the sensitivities of mortality to  $NO_x/SO_2$  emissions increase sharply/

marginally with increasing reduction ratio of  $NO_x/SO_2$ . Andersson et al. (2009) evaluated the sources of premature deaths in Europe, and concluded that primary  $PM_{2.5}$  was associated with more premature deaths than secondary inorganic aerosol (SIA), indicating that it might be more efficient for protecting public health to decrease primary PM emissions than to decrease precursors of SIA. This is in line with our conclusion that primary  $PM_{2.5}$  emissions make the largest contribution to  $PM_{2.5}$ -related mortality and thus should be stringently controlled.

#### 4. Conclusion and implications

In this study, we assessed the nonlinear relationships between  $PM_{2.5}$ -related mortality and air pollutant emissions in the BTH region





**Fig. 6.** Sensitivity of annual mortality caused by long-term exposure to  $PM_{2.5}$  in Beijing to stepped control of individual/all air pollutants from various regions within the BTH. The meanings of two axes and colored bars are the same as in Fig. 3. The black dotted line denotes the sensitivity of mortality when emissions from all five regions are controlled simultaneously, while the hollow triangle dotted line denotes the sensitivity when emissions from regions except Beijing are controlled simultaneously.

by integrating the CMAQ/2D-VBS model, the ERSM technique, and the CRFs.

The annual premature mortalities attributable to long-term and short-term exposures to  $PM_{2.5}$  are estimated at 130.1 thousand and 18.7 thousand, respectively, in the BTH region. The mortalities due to both long-term and short-term  $PM_{2.5}$  exposures are most sensitive to the reduction of primary inorganic  $PM_{2.5}$  emissions. The sensitivity of long-term mortality to primary inorganic  $PM_{2.5}$  increases significantly with reduction ratio, as a result of the curvilinear IER function. In winter, the primary inorganic  $PM_{2.5}$  emissions, especially those from residential and commercial sources, contribute much more to short-term mortality than in other seasons. We suggest a sharp reduction in the emissions of primary  $PM_{2.5}$  over the BTH region, with a particular focus placed on those from the residential and commercial sectors in winter, which have been largely neglected in the country's control policies until recently.

Among the precursors of  $PM_{2.5}$ , the  $PM_{2.5}$ -related mortality is primarily sensitive to emissions of  $NH_3$ , NMVOC+IVOC, and POA. Their relative importance differs by region and reduction ratio. The sensitivities of mortality to POA, NMVOC+IVOC and  $SO_2$  do not change much with reduction ratio, whereas the sensitivities to  $NH_3$  and  $NO_x$  increase significantly with the increase of reduction ratio. The control of  $NO_x$  emissions in BTH tends to increase mortality at small reduction ratio and reduce mortality at large reductions; however, a nationwide  $NO_x$  emission control always reduces  $PM_{2.5}$ -related mortality in the BTH region. The sensitivities of short-term mortality to gaseous precursors are generally larger in summer than in winter. Substantial control policies should be implemented for  $NO_x$  and  $NH_3$  emissions in the BTH region. For  $NO_x$ , stringent controls on national scale with an emphasis on summertime emissions are suggested to avoid possible side effects and to achieve maximal health benefits.

Regarding the emissions from different regions, the annual  $PM_{2.5}$ -related mortality in Beijing is most sensitive to local emissions. Over 60% of the contributions from emissions of primary inorganic  $PM_{2.5}$ , POA, and  $SO_2$  to long-term mortality in Beijing are attributed to local emissions. For  $NH_3$  and NMVOC+IVOC, local emissions account for 50% and one third, respectively. Therefore, the control of local emissions

is of primary importance for the reduction of  $PM_{2.5}$ -related mortality in a specific region. When emissions from local and nonlocal emissions or those of multiple pollutants are controlled simultaneously, the overall sensitivity of mortality due to long-term  $PM_{2.5}$  exposure exceeds the arithmetic sum of the sensitivities to emissions of each individual region/pollutant, and the differences are more pronounced for larger reduction ratios. Therefore, in the long run, a multi-pollutant, multi-sector and regional joint control strategy is recommended wherever possible in order to maximize the marginal benefits of public health. In contrast, with respect to short-term mortality, the overall sensitivity resembles the sum of the sensitivities to individual pollutants or regions. For this reason, the jointly control strategy may not be vital for temporary control measures to reduce the mortality induced by severe pollution events; instead, more precisely targeted measures should be developed according to the characteristics of each individual event.

### Competing interest statement

The authors declare no conflict of interests.

### CRediT authorship contribution statement

**Bin Zhao:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Shuxiao Wang:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing - original draft, Writing - review & editing. **Dian Ding:** Validation, Visualization, Writing - original draft, Writing - review & editing. **Wenjing Wu:** Formal analysis, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Xing Chang:** Validation, Visualization, Writing - original draft, Writing - review & editing. **Jiandong Wang:** Investigation. **Jia Xing:** Validation, Visualization, Writing - original draft, Writing - review & editing. **Carey Jang:** Software, Writing - original draft, Writing - review & editing. **Joshua S. Fu:** Software, Writing - original draft, Writing - review & editing. **Yun Zhu:** Writing - original draft, Writing - review & editing. **Mei Zheng:** Validation,

Writing - original draft, Writing - review & editing. **Yu Gu:** Validation, Writing - original draft, Writing - review & editing.

## Acknowledgements

This study has been supported by National Natural Science Foundation of China (21625701) and National Research Program for Key Issues in Air Pollution Control (DQGG0301). B.Z. and Y.G. are supported by NSF AGS-1701526 and UCLA Grand Challenge Grant 50958. Y.G. also acknowledges the support of the Natural Science Foundation of Jiangsu Province, China (No. BK20171230). Our work is completed on the “Explorer 100” cluster system of Tsinghua National Laboratory for Information Science and Technology.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.01.169>.

## References

- Andersson, C., Bergstrom, R., Johansson, C., 2009. Population exposure and mortality due to regional background PM in Europe - Long-term simulations of source region and shipping contributions. *Atmos. Environ.* 43, 3614–3620. <https://doi.org/10.1016/j.atmosenv.2009.03.040>.
- Apte, J.S., Marshall, J.D., Cohen, A.J., Brauer, M., 2015. Addressing global mortality from ambient PM<sub>2.5</sub>. *Environ. Sci. Technol.* 49, 8057–8066. <https://doi.org/10.1021/acs.est.5b01236>.
- Burnett, R.T., Pope, C.A., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., Anderson, H.R., Smith, K.R., Balmes, J.R., Bruce, N.G., Kan, H.D., Laden, F., Pruss-Ustun, A., Michelle, C.T., Gapstur, S.M., Diver, W.R., Cohen, A., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Persp.* 122, 397–403. <https://doi.org/10.1289/Ehp.1307049>.
- Burnett, R., Chen, H., Szyszkowicz, M., 2018. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *P. Natl. Acad. Sci. USA* 115, 9592–9597. <https://doi.org/10.1073/pnas.1803222115>.
- Cai, S.Y., Wang, Y.J., Zhao, B., Wang, S.X., Chang, X., Hao, J.M., 2017. The impact of the “Air pollution prevention and control action plan” on PM<sub>2.5</sub> concentrations in Jing-Jin-Ji region during 2012–2020. *Sci. Total. Environ.* 580, 197–209. <https://doi.org/10.1016/j.scitotenv.2016.11.188>.
- Chang, X., Wang, S.X., Zhao, B., Cai, S.Y., Hao, J.M., 2018. Assessment of inter-city transport of particulate matter in the Beijing-Tianjin-Hebei region. *Atmos. Chem. Phys.* 18, 4843–4858. <https://doi.org/10.5194/acp-18-4843-2018>.
- Chen, R.J., Li, Y., Ma, Y.J., Pan, G.W., Zeng, G., Xu, X.H., Chen, B.H., Kan, H.D., 2011. Coarse particles and mortality in three Chinese cities: the China air pollution and health effects study (CAPES). *Sci. Total. Environ.* 409, 4934–4938. <https://doi.org/10.1016/j.scitotenv.2011.08.058>.
- Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, R., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shadick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015. *Lancet* 389, 1907–1918. [https://doi.org/10.1016/s0140-6736\(17\)30505-6](https://doi.org/10.1016/s0140-6736(17)30505-6).
- Dominici, F., McDermott, A., Zeger, S.L., Samet, J.M., 2002. On the use of generalized additive models in time-series studies of air pollution and health. *Am. J. Epidemiol.* 156, 193–203. <https://doi.org/10.1093/aje/kwf062>.
- Dong, X.Y., Li, J., Fu, J.S., Gao, Y., Huang, K., Zhuang, G.S., 2014. Inorganic aerosols responses to emission changes in Yangtze River Delta, China. *Sci. Total. Environ.* 481, 522–532. <https://doi.org/10.1016/j.scitotenv.2014.02.076>.
- Fann, N., Baker, K.R., Fulcher, C.M., 2012. Characterizing the PM<sub>2.5</sub>-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S. *Environ. Int.* 49, 141–151. <https://doi.org/10.1016/j.envint.2012.08.017>.
- Fu, J.S., Dong, X.Y., Gao, Y., Wong, D.C., Lam, Y.F., 2012. Sensitivity and linearity analysis of ozone in East Asia: the effects of domestic emission and intercontinental transport. *J. Air. Waste Manag.* 62. <https://doi.org/10.1080/10962247.2012.699014>.
- GBD MAPS Working Group, 2016. Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China. Special Report 20, available at: <https://www.healthdata.org/publication/burden-disease-attributable-coal-burning-and-other-air-pollution-sources-china> Health Effects Institute, Boston, MA.
- Global Burden of Disease Collaborative Network, 2017. Global burden of disease study 2016 (GBD 2016) results tool. available from: <http://ghdx.healthdata.org/gbd-results-tool> Institute for Health Metrics and Evaluation (IHME), Seattle, United States.
- Global Road Safety Facility, The World Bank, Institute for Health Metrics and Evaluation (IHME), University of Washington, 2014. Transport for Health: The Global Burden of Disease from Motorized Road Transport (Web Appendix). available at: [http://www.healthdata.org/sites/default/files/policy\\_report/2014/Transport4Health/IHME\\_Transport4Health\\_WebAppendix.pdf](http://www.healthdata.org/sites/default/files/policy_report/2014/Transport4Health/IHME_Transport4Health_WebAppendix.pdf) The World Bank, Washington, DC.
- Gordon, T.D., Presto, A.A., May, A.A., Nguyen, N.T., Lipsky, E.M., Donahue, N.M., Gutierrez, A., Zhang, M., Maddox, C., Rieger, P., Chattopadhyay, S., Maldonado, H., Maricq, M.M., Robinson, A.L., 2014. Secondary organic aerosol formation exceeds primary particulate matter emissions for light-duty gasoline vehicles. *Atmos. Chem. Phys.* 14, 4661–4678. <https://doi.org/10.5194/acp-14-4661-2014>.
- Guenther, A., Karl, T., Harley, P., Wiedinmyer, C., Palmer, P.I., Geron, C., 2006. Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmos. Chem. Phys.* 6, 3181–3210.
- Heo, J., Adams, P.J., Gao, H.O., 2016. Public health costs of primary PM<sub>2.5</sub> and inorganic PM<sub>2.5</sub> precursor emissions in the United States. *Environ. Sci. Technol.* 50, 6061–6070. <https://doi.org/10.1021/acs.est.5b06125>.
- Hu, J.L., Huang, L., Chen, M.D., Liao, H., Zhang, H.L., Wang, S.X., Zhang, Q., Ying, Q., 2017. Premature mortality attributable to particulate matter in China: source contributions and responses to reductions. *Environ. Sci. Technol.* 51, 9950–9959. <https://doi.org/10.1021/acs.est.7b03193>.
- Huang, D.S., Zhang, S.Q., 2013. Health benefit evaluation for PM<sub>2.5</sub> pollution control in Beijing-Tianjin-Hebei region of China. *Chin. Environ. Sci.* 33, 166–174.
- Jathar, S.H., Gordon, T.D., Hennigan, C.J., Pye, H.O.T., Pouliot, G., Adams, P.J., Donahue, N.M., Robinson, A.L., 2014. Unspecified organic emissions from combustion sources and their influence on the secondary organic aerosol budget in the United States. *P. Natl. Acad. Sci. USA* 111, 10473–10478. <https://doi.org/10.1073/pnas.1323740111>.
- Kan, H.D., Chen, B.H., 2004. Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. *Sci. Total. Environ.* 322, 71–79. <https://doi.org/10.1016/j.scitotenv.2003.09.010>.
- Kan, H.D., London, S.J., Chen, G.H., Zhang, Y.H., Song, G.X., Zhao, N.Q., Jiang, L.L., Chen, B.H., 2008. Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in Shanghai, China: The Public Health and Air Pollution in Asia (PAPA) study. *Environ. Health Persp.* 116, 1183–1188. <https://doi.org/10.1289/ehp.10851>.
- Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* 525, 367–371. <https://doi.org/10.1038/nature15371>.
- Li, M., Zhang, Q., Kurokawa, J., Woo, J.H., He, K.B., Lu, Z., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., Cheng, Y.F., Hong, C.P., Huo, H., Jiang, X.J., Kang, S.C., Liu, F., Su, H., Zheng, B., 2015. MIX: a mosaic Asian anthropogenic emission inventory for the MICS-Asia and the HTAP projects. *Atmos. Chem. Phys. Discuss.* 15, 34813–34869. <https://doi.org/10.5194/acdp-15-34813-2015>.
- Lv, L.Y., Li, H.Y., 2016. Health economic evaluation of PM<sub>10</sub> and PM<sub>2.5</sub> pollution in Beijing-Tianjin-Hebei region of China. *Acta Sci. Nat. Univ. Nankaiensis* 49, 69–77.
- Martenies, S.E., Wilkins, D., Batterman, S.A., 2015. Health impact metrics for air pollution management strategies. *Environ. Int.* 85, 84–95. <https://doi.org/10.1016/j.envint.2015.08.013>.
- National Health and Family Planning Commission of China, 2015. *China Health and Family Planning Statistics Yearbook 2015*. Peking Union Medical College Press, Beijing, China.
- Oak Ridge National Laboratory, 2016. LandScan dataset 2016. available at: <https://web.ornl.gov/sci/landscan/>.
- Shang, Y., Sun, Z.W., Cao, J.J., Wang, X.M., Zhong, L.J., Bi, X.H., Li, H., Liu, W.X., 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. <https://doi.org/10.1016/j.envint.2013.01.010>.
- Tuomisto, J.T., Wilson, A., Evans, J.S., Tainio, M., 2008. Uncertainty in mortality response to airborne fine particulate matter: combining European air pollution experts. *Reliab. Eng. Syst. Saf.* 93, 732–744. <https://doi.org/10.1016/j.res.2007.03.002>.
- Wang, S.X., Xing, J., Jang, C.R., Zhu, Y., Fu, J.S., Hao, J.M., 2011. Impact assessment of ammonia emissions on inorganic aerosols in east China using response surface modeling technique. *Environ. Sci. Technol.* 45, 9293–9300. <https://doi.org/10.1021/Es2022347>.
- Wang, S.X., Zhao, B., Cai, S.Y., Klimont, Z., Nielsen, C.P., Morikawa, T., Woo, J.H., Kim, Y., Fu, X., Xu, J.Y., Hao, J.M., He, K.B., 2014. Emission trends and mitigation options for air pollutants in East Asia. *Atmos. Chem. Phys.* 14, 6571–6603. <https://doi.org/10.5194/acp-14-6571-2014>.
- Wang, J., Wang, S., Voorhees, A.S., Zhao, B., Jang, C., Jiang, J., Fu, J.S., Ding, D., Zhu, Y., Hao, J., 2015. Assessment of short-term PM<sub>2.5</sub>-related mortality due to different emission sources in the Yangtze River Delta, China. *Atmos. Environ.* 123, 440–448. <https://doi.org/10.1016/j.atmosenv.2015.05.060>.
- Wang, J.D., Zhao, B., Wang, S.X., Yang, F.M., Xing, J., Morawska, L., Ding, A.J., Kulmala, M., Kerminen, V.M., Kujansuu, J., Wang, Z.F., Ding, D.A., Zhang, X.Y., Wang, H.B., Tian, M., Petaja, T., Jiang, J.K., Hao, J.M., 2017. Particulate matter pollution over China and the effects of control policies. *Sci. Total. Environ.* 584, 426–447. <https://doi.org/10.1016/j.scitotenv.2017.01.027>.
- Wu, W.J., 2016. Health Effect Attributed to Ambient Fine Particle Pollution in the Beijing-Tianjin-Hebei Region and its Source Apportionment. M.S. thesis. School of Environment, Tsinghua University, Beijing, China 98 pp.
- Wu, W.J., Zhao, B., Wang, S.X., Hao, J.M., 2017. Ozone and secondary organic aerosol formation potential from anthropogenic volatile organic compounds emissions in China. *J. Environ. Sci.* 53, 224–237. <https://doi.org/10.1016/j.jes.2016.03.025>.
- Xing, J., Wang, S.X., Jang, C., Zhu, Y., Hao, J.M., 2011. Nonlinear response of ozone to precursor emission changes in China: a modeling study using response surface methodology. *Atmos. Chem. Phys.* 11, 5027–5044. <https://doi.org/10.5194/acp-11-5027-2011>.
- Xing, J., Wang, S.X., Zhao, B., Wu, W.J., Ding, D.A., Jang, C., Zhu, Y., Chang, X., Wang, J.D., Zhang, F.F., Hao, J.M., 2017. Quantifying nonlinear multiregional contributions to ozone and fine particles using an updated response surface modeling technique. *Environ. Sci. Technol.* 51, 11788–11798. <https://doi.org/10.1021/acs.est.7b01975>.
- Zhao, B., Wang, S.X., Wang, J.D., Fu, J.S., Liu, T.H., Xu, J.Y., Fu, X., Hao, J.M., 2013. Impact of national NO<sub>x</sub> and SO<sub>2</sub> control policies on particulate matter pollution in China. *Atmos. Environ.* 77, 453–463. <https://doi.org/10.1016/j.atmosenv.2013.05.012>.

- Zhao, B., Wang, S.X., Xing, J., Fu, K., Fu, J.S., Jang, C., Zhu, Y., Dong, X.Y., Gao, Y., Wu, W.J., Wang, J.D., Hao, J.M., 2015. Assessing the nonlinear response of fine particles to precursor emissions: development and application of an extended response surface modeling technique v1.0. *Geosci. Model. Dev.* 8, 115–128. <https://doi.org/10.5194/gmd-8-115-2015>.
- Zhao, B., Wang, S.X., Donahue, N.M., Jathar, S.H., Huang, X.F., Wu, W.J., Hao, J.M., Robinson, A.L., 2016. Quantifying the effect of organic aerosol aging and intermediate-volatility emissions on regional-scale aerosol pollution in China. *Sci. Rep.-Uk* 6, 28815. <https://doi.org/10.1038/srep28815>.
- Zhao, B., Wu, W.J., Wang, S.X., Xing, J., Chang, X., Liou, K.N., Jiang, J.H., Gu, Y., Jang, C., Fu, J.S., Zhu, Y., Wang, J.D., Lin, Y., Hao, J.M., 2017. A modeling study of the nonlinear response of fine particles to air pollutant emissions in the Beijing-Tianjin-Hebei region. *Atmos. Chem. Phys.* 17, 12031–12050. <https://doi.org/10.5194/acp-17-12031-2017>.
- Zhao, B., Jiang, J.H., Diner, D.J., Su, H., Gu, Y., Liou, K.N., Jiang, Z., Huang, L., Takano, Y., Fan, X.H., Omar, A.H., 2018a. Intra-annual variations of regional aerosol optical depth, vertical distribution, and particle types from multiple satellite and ground-based observational datasets. *Atmos. Chem. Phys.* 18, 11247–11260. <https://doi.org/10.5194/acp-18-11247-2018>.
- Zhao, B., Zheng, H., Wang, S., Smith, K.R., Lu, X., Aunan, K., Gu, Y., Wang, Y., Ding, D., Xing, J., Fu, X., Yang, X., Liou, K.N., Hao, J., 2018b. Change in household fuels dominates the decrease in PM<sub>2.5</sub> exposure and premature mortality in China in 2005–2015. *P. Natl. Acad. Sci. USA* 115, 12401–12406.
- Zheng, H.T., Cai, S.Y., Wang, S.X., Zhao, B., Chang, X., Hao, J.M., 2018. Development of a unit-based industrial emission inventory in the Beijing-Tianjin-Hebei region and resulting improvement in air quality modeling. *Atmos. Chem. Phys. Discuss.* <https://doi.org/10.5194/acp-2018-858>.