



# The effects of anthropogenic dust on fine particulate matter in Beijing-Tianjin-Hebei region

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## ABSTRACT

The Beijing-Tianjin-Hebei (BTH) region and its surrounding provinces in China represent a key zone for combating air pollution, with the primary objective of reducing fine particulate matter (PM<sub>2.5</sub>). Anthropogenic fugitive, combustion, and industrial dust (AFCID) is a significant anthropogenic dust source in the composition of PM<sub>2.5</sub>, which is often underrepresented in the global models. This study employed the GEOS-Chem model to quantitatively assess the effects of AFCID on PM<sub>2.5</sub> in BTH and its surrounding provinces in 2020. The Global Exposure Mortality Model (GEMM) and the Integrated Exposure-Response Model (IER) were further employed to estimate the additional number of PM<sub>2.5</sub>-related premature deaths due to AFCID emissions. The inclusion of AFCID emissions reduced the discrepancies in modeled versus observed daily mean PM<sub>2.5</sub> values in the five provinces (Beijing, Tianjin, Hebei, Henan, and Shandong) in 2020, with decreases of the normalized mean bias by 13.30 %–18.46 % and the normalized mean error by 1.14 %–6.94 %. The AFCID emissions contributed significantly to PM<sub>2.5</sub> concentrations in the five provinces, with the averaged annual and seasonal contributions ranging from 6.0 to 8.8  $\mu\text{g m}^{-3}$  (17.2 %–21.1 %) and 4.2–12.4  $\mu\text{g m}^{-3}$  (17.1 %–22.8 %), respectively. In terms of the numbers of PM<sub>2.5</sub>-related premature deaths additionally due to AFCID emissions in the five provinces in 2020 were approximately from 3.6 thousand to 19.4 thousand (8.8 %–14.3 %) and 2.5 thousand to 12.8 thousand (7.3 %–13.0 %), respectively, calculated by GEMM and IER. Our study would offer a scientific foundation for understanding the compositions of PM<sub>2.5</sub> in BTH, as well as for formulating corresponding emission reduction strategies.

## 1. Introduction

As economic growth and the acceleration of urbanization, the issue of air pollution in the Beijing-Tianjin-Hebei (BTH) in China has become increasingly prominent. The 2023 Action Plan for Continuous Improvement of Air Quality states that the primary course of action for China is the reduction of fine particulate matter (PM<sub>2.5</sub>) concentrations and identifies the BTH and its neighboring regions as critical areas (State Council of China, 2023). PM<sub>2.5</sub> has significant impact on human health (Du et al., 2020), diminishes atmospheric visibility (Krittanawong et al., 2023), disrupts the atmosphere radiation balance, and contributes to climate change (Liu et al., 2020; Sun et al., 2019; Pui et al., 2014). Effective management of PM<sub>2.5</sub> has become a critical topic in China's

environmental protection efforts, and a thorough understanding of PM<sub>2.5</sub> is essential for enhancing environmental quality, stabilizing the climate, and ensuring human health.

PM<sub>2.5</sub> sources are classified as natural and anthropogenic, with the latter playing a key factor in urban PM<sub>2.5</sub> (Zhai et al., 2019). Du et al. (2024) employed the Community Multiscale Air Quality model for an investigation of PM<sub>2.5</sub> sources in 117 China cities from 2013 to 2018, and indicated that anthropogenic sources accounted for more than 76.62 % of the total PM<sub>2.5</sub>. Anthropogenic fugitive, combustion, and industrial dust (AFCID) is an important anthropogenic dust source in the composition of PM<sub>2.5</sub>, which originates from various anthropogenic activities, including coal combustion processes (fly ash), industrial operations, as well as infrastructure and building constructions (Philip

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et al., 2017). Many studies have shown that the AFCID emissions are significant contributors to PM<sub>2.5</sub> pollution in urban regions. Philip et al. (2017) noted that including AFCID emissions in GEOS-Chem model simulations increased the two-year (2014–2015) annual average PM<sub>2.5</sub> levels across East and South Asia by 2–16 μg m<sup>-3</sup>. Venkataraman et al. (2020) employed the WRF-Chem model to find that anthropogenic mineral matter (largely coal fly-ash) contributed to the mean PM<sub>2.5</sub> values by 22.1 % and 16.4 % in the two Indian cities during October to November 2019. Zhao et al. (2019) pointed out that coal-fired fly ash was one of the common components of PM<sub>2.5</sub>, and found that coal combustion dust accounted for 8.6 % of total PM<sub>2.5</sub> concentrations in Jiayang City during October 2016 to November 2017 by employing the positive matrix factorization model. Ou et al. (2022) found that fly ash accounted for 19.74 % of the total PM<sub>2.5</sub> concentrations using scanning electron microscopy in the Huainan from December 2016 to May 2017. Zhang et al. (2020), using the Chemical Mass Balance model, found that steel dust and construction dust accounted for 7 % and 6 %, respectively, of the daily PM<sub>2.5</sub> concentrations across five Laiwu City sites in 2016.

AFCID significantly contributes to PM<sub>2.5</sub> concentrations and associated health risks, and studies have confirmed severe health impacts from long-term AFCID exposure (Xia et al., 2022). Wang et al. (2023) reported that prolonged exposure to coal combustion particles increased respiratory mortality by 15 %, with construction dust also showing clear associations with higher risks of respiratory diseases and cancer. For vulnerable populations, Shi et al. (2020) found that children living near incineration facilities faced lifetime cancer risks 62 times higher than acceptable thresholds, corresponding to about 1 additional cancer case per 1600 exposed children. These findings highlight the critical need for comprehensive emission assessments and quantitative health risk analyses.

However, the AFCID emissions are often an ignored part of modeling studies, partially missing or severely underrepresented in global model (Chappell et al., 2023). Most dust simulations focus only on natural dust sources and neglect anthropogenic dust sources, which is important for developing countries like China and India where larger amounts of anthropogenic dust are emitted but still not well measured (Chen et al., 2019). Adding AFCID emissions to the model can significantly reduce the model's deviation from the observed data (Wang et al., 2022), and would also enable more precise assessments of how aerosols affect atmospheric quality and public health (Jeong and Park, 2019). Philip et al. (2017), employing the GEOS-Chem model, found that adding AFCID emissions reduced the deviation between annual average observed and modeled PM<sub>2.5</sub> concentrations during 2014–2015 from 7 % to 17 % globally, and improved the correlation coefficient (*r*) of modeled PM<sub>2.5</sub> dust mass concentrations and measurements of the Surface Particulate Matter Network from 0.06 to 0.66. Jeong and Park (2019) conducted particulate matter simulations for China and South Korea through the GEOS-Chem model during January to March 2016 and found that including AFCID emissions increased the *r* between simulated and observed national daily mean PM<sub>2.5</sub> from 0.72 to 0.74.

The PM<sub>2.5</sub> emission inventory in the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC, 2020), currently the most widely used in China, represents the PM<sub>2.5</sub> anthropogenic primary emissions (Zheng et al., 2021). The PM<sub>2.5</sub> primary emissions consist largely of fine particulate matter released alongside black carbon (BC) and organic carbon (OC) during combustion processes (Zhang et al., 2016). According to Philip et al. (2017), MEIC PM<sub>2.5</sub> emissions need to remove particulate organic mass (OM), BC, and sulfate for the calculation of AFCID emissions, and the remaining primary emission residue can be a better substitute for anthropogenic dust emissions. Including the AFCID emissions into the global model would compensate for the absence of anthropogenic dust, then enhance the precision of the simulation outcomes.

It is clear that the AFCID emissions contribute significantly to PM<sub>2.5</sub> concentrations and need to be further developed and more widely used in global models. Although previous studies have described the sources

of AFCID emissions and their impact, few studies have employed models to access the influence of AFCID emissions on PM<sub>2.5</sub> in the BTH. The present study thus primarily aims to: (1) Improve the accuracy of PM<sub>2.5</sub> simulations in the GEOS-Chem model by incorporating an updated China AFCID emission inventory in 2020, following Philip et al. (2017); (2) Quantify the contribution of AFCID emissions to PM<sub>2.5</sub> concentrations in the BTH region; (3) Assess the PM<sub>2.5</sub>-related health hazards caused by AFCID emissions in the BTH. To achieve these objectives, we employed the GEOS-Chem model and two health risk calculation models (the Global Exposure Mortality Model, GEMM and the Integrated Exposure-Response Model, IER) to quantify the influence of PM<sub>2.5</sub> anthropogenic dust in the BTH in 2020 under scenarios with and without AFCID emissions. Our study thus would offer a scientific foundation for understanding the sources of PM<sub>2.5</sub> in the BTH, as well as for formulating corresponding emission reduction strategies.

## 2. Methods

### 2.1. GEOS-Chem

The GEOS-Chem model (GEOS-Chem v12-09, 2020) developed by Harvard University is used in the present study. We conduct a global simulation with the spatial resolution of 2° × 2.5° horizontally and 47 levels vertically, and nested simulations over the Asian region (60°–150°E, 11°S–55°N) at a horizontal resolution of 0.5° × 0.625°, driven by MERRA2 meteorological data. The model unilaterally provides chemical concentration boundaries to the nested grid at 3-h intervals.

GEOS-Chem has been employed broadly in the modeling of PM<sub>2.5</sub>. Following the commonly used methodology, we calculate the simulated hourly PM<sub>2.5</sub> concentration under the condition of 35 % relative humidity. The substances utilized in this calculation include ammonium, nitrate, sulfate, BC, OC, and dust aerosol. The GEOS-Chem mineral dust simulation follows the Dust Entrainment and Deposition scheme of Zender et al. (2023a, 2023b). Zhang et al. (2013) optimized the dust particle size distribution within the model, through which the current standard GEOS-Chem model categorizes mineral dust into 0.2–2.0, 2.0–3.6, 3.6–6.0, and 6.0–12.0 μm diameters. Aerosols from AFCID emissions are regarded as identical to mineral dust (Jeong and Park, 2019). For ease of computation, the AFCID dust is defined as the finest particle size fraction of GEOS-Chem dust.

### 2.2. Emission inventories and simulations

The anthropogenic emissions are from the Community Emission Data System (CEDS) (Feng et al., 2020) for the global scope at a spatial resolution of 0.5° × 0.5°, and from the MEIC inventory for 2020 (Geng et al., 2024) at a spatial resolution of 0.25° × 0.25° for the Chinese region. The biomass burning emission inventories are from the Global Fire Emissions Database (GFEDv4) (van der Werf et al., 2017) for 2019, with a spatial resolution of 0.25° × 0.25°. Flash NO<sub>x</sub> emissions are described in detail in the studies by Murray et al. (2012). The algorithm for soil NO<sub>x</sub> emissions is initially stated by Yienger and Levy (1995).

The AFCID is a global monthly inventory of anthropogenic dust emissions described by Philip et al. (2017). The original AFCID emissions in China region are based on PM<sub>2.5</sub> emissions from the MEIC inventory for 2012, and we update the China AFCID emissions using the MEIC PM<sub>2.5</sub> emission inventory for 2020. The AFCID emissions in India are from the local emissions data for 2013, and the emissions for the other world region are from the global emissions of anthropogenic primary PM<sub>2.5</sub> in 2015 developed by Klimont et al. (2017).

Following Philip et al. (2017), we update the original AFCID emission inventory from 2012 to 2020 using the 2020 MEIC PM<sub>2.5</sub> emission inventory. Specifically, we substitute 1.6 (a common ratio used in urban areas) times OC for OM (Chan et al., 2009; Xiang et al., 2017), and the primary sulfate is replaced with 3 % sulfur dioxide. Finally, the MEIC

PM<sub>2.5</sub> emission inventory is modified to exclude OM, BC, and primary sulfate to represent AFCID emissions. Thus, the AFCID emissions are calculated as:

$$\text{AFCID} = \text{MEIC.PM}_{2.5} - \text{OM} - \text{BC} - \text{primary sulfate} \quad (1)$$

The AFCID emission inventory has some uncertainties, primarily from uncertainties in the MEIC inventory and the methodological limitations. As indicated by Zhang et al. (2017), the estimated uncertainties in MEIC emission are approximately ±130 % for PM<sub>2.5</sub>, ±258 % for OC, ±208 % for BC, and ±12 % for SO<sub>2</sub>, which directly affect the AFCID calculations. Furthermore, due to measurement limitations, MEIC does not include urban fugitive road dust emissions (Lei et al., 2011; Zhang et al., 2016), which may cause further bias and potential underestimation in the estimated contribution from urban anthropogenic dust. As discussed in studies like Cui et al. (2019), the current lack of long-term effective observational data for anthropogenic dust emissions hinders effective quantification and verification of the uncertainties in AFCID emissions.

In the present study, two sensitivity tests are conducted through the GEOS-Chem: (1) simulation without the AFCID emissions (BASE simulation); and (2) simulation with the addition of the AFCID emissions (AFCID simulation). To ensure the feasibility of the analysis, the two sensitivity simulations differ solely in whether AFCID emissions are incorporated, and all other settings are identical. By analyzing the differences between the two simulation results, we aim to assess whether the inclusion of AFCID emissions will enhance the accuracy of the model simulation of PM<sub>2.5</sub> concentrations and evaluate the effects of AFCID emissions on PM<sub>2.5</sub> and the related health hazards. Considering seasonal influences on PM<sub>2.5</sub>, we define March to May in 2020 as spring, June to August as summer, September to November as autumn, and the remaining months of December, January, and February as winter, to investigate seasonal variations in the impacts of AFCID emissions. Additionally, the heating season is defined as January to March and November to December 2020, following Yan et al. (2023).

### 2.3. PM<sub>2.5</sub> observations

PM<sub>2.5</sub> surface observations are acquired from the China National Environmental Monitoring Center (CNEMC, 2020), specifically from 222 national monitoring network stations in the BTH and its two neighboring provinces (Henan and Shandong). For the model simulation verification, the observed PM<sub>2.5</sub> concentrations within BTH and its surrounding provinces are calculated by averaging the PM<sub>2.5</sub> concentrations collected from all national observation stations located within that particular province/city. For comparison, the sampled model gridded data at the corresponding locations of observation stations are also averaged for each province/city.

### 2.4. Health impact assessment of PM<sub>2.5</sub> exposures

Previous studies have identified long-term PM<sub>2.5</sub> exposure as a major hazard to human health (Maji, 2020; Cai et al., 2021). High PM<sub>2.5</sub> levels in the BTH make it imperative to study the PM<sub>2.5</sub> sources and the corresponding health risks. Including AFCID emissions would improve the accuracy of PM<sub>2.5</sub> simulation and the assessments of the corresponding health impacts. We use the GEMM model by Burnett et al. (2018) and the IER model by Burnett et al. (2014), which are widely used in studies on PM<sub>2.5</sub> health exposures (Dhital et al., 2024; Tang et al., 2022). The GEMM model provides more accurate calculations for severely polluted regions, like China (Chen et al., 2020), while the IER model is more widely employed in the official global burden of disease (GBD) assessments and World Health Organization mortality estimations (Dang and Liao, 2019a). We select the GEMM 5-COD model and IER model for estimating the causes of death for five diseases: ischemic heart disease (IHD), lower respiratory infections (LRI), lung cancer (LC), chronic obstructive pulmonary disease (COPD), and stroke. The specific formula

is as follows:

$$\Delta \text{Mortality} = \text{Pop} \times y_0 \times \frac{RR_{(c)} - 1}{RR_{(c)}} \quad (2)$$

where ΔMortality is the premature mortality; Pop is the population of each area with data sourced from 2020 Population Census of China (National Bureau of Statistics of China, 2021), and we follow Burnett et al. (2018) to count only adults aged 25 and over, y<sub>0</sub> represents the fatality rate of a particular disease collected from the GBD statistics for 2020 (GBD, 2020); RR<sub>(c)</sub> serves as relative risk, and its formula in GEMM 5-COD model is as follows:

$$RR_{(c)} = \exp \left[ \frac{\theta \times \ln \left( 1 + \frac{c - c_0}{\alpha} \right)}{1 + \exp \left( -\frac{c - c_0 - \mu}{\nu} \right)} \right] \quad (3)$$

where c is the 2020 annual mean PM<sub>2.5</sub> value; c<sub>0</sub> is 2.4 μg m<sup>-3</sup>, which is a harmless concentration of PM<sub>2.5</sub> documented by Burnett et al. (2018); while the values of parameters θ, α, μ, ν are given in Burnett et al. (2018).

And the formula of RR<sub>(c)</sub> in IER model is as follows:

$$RR_{(c)} = \begin{cases} \alpha \{ 1 - \exp[-\gamma(c - c_0)^\delta] \} + 1 & c > c_0 \\ 1 & c \leq c_0 \end{cases} \quad (4)$$

where c in formula ④ is same as c in formula ③; c<sub>0</sub> is 5.8–8.0 μg m<sup>-3</sup>, representing the theoretical harmless values of PM<sub>2.5</sub> according to Burnett et al. (2014), with different values for different diseases; while the values of parameters α, γ, δ are referred to Burnett et al. (2014).

## 3. Results and discussion

### 3.1. AFCID emissions inventory

The spatial distribution of AFCID emissions across BTH and its neighboring provinces during 2020 is presented in Fig. 1. According to the Action Plan for the Continuous Enhancement of Air Quality (State Council of China, 2023), the BTH, together with its two neighboring provinces (Henan and Shandong), constitutes a pivotal zone for air pollution control, as outlined in Fig. 1 by the purple line. The total

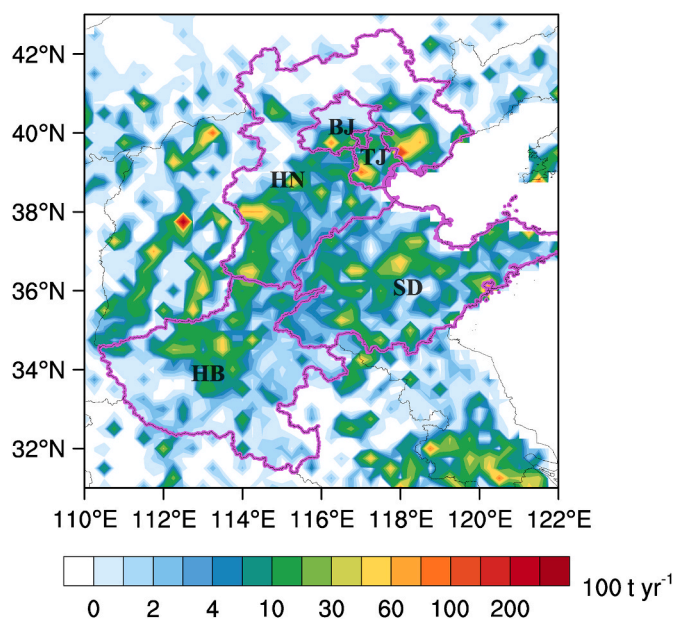


Fig. 1. Distribution of annual AFCID emissions in the BTH and its neighboring areas (outlined in purple) in 2020. BJ: Beijing, TJ: Tianjin, HN: Henan, HB: Hebei, SD: Shandong.

annual AFCID emissions in China in 2020 are 1.89 Tg, with the BTH and its neighboring areas accounting for 0.68 Tg. It is noteworthy that in the BTH region, high AFCID emissions are observed in the southeastern Beijing, the southeastern Tianjin, and the eastern and southern areas of Hebei Province. Moreover, AFCID emissions in the BTH and its neighboring provinces show seasonal contributions of 0.16 Tg in spring, 0.18 Tg in summer, 0.18 Tg in autumn, and 0.16 Tg in winter in 2020. In China, the novel coronavirus disease (Covid-19) lockdown significantly reduced anthropogenic emissions during January to March in 2020, with the February showing the most significant reduction (Zheng et al., 2021), which caused a slight decrease in AFCID emissions in spring and a marked reduction in winter.

### 3.2. Model validation

Some studies show that the GEOS-Chem performs reasonably in  $PM_{2.5}$  simulation (Li et al., 2020; Xu et al., 2023; Zhang et al., 2022). The distribution of annual mean  $PM_{2.5}$  values in the BTH and its neighboring provinces in 2020 under the GEOS-Chem simulation and the difference between the AFCID and BASE simulations are shown in Fig. 2. The GEOS-Chem model accurately describes the distribution of  $PM_{2.5}$  levels, showing higher  $PM_{2.5}$  levels in the southern part (exceeding the national secondary standard of  $35 \mu g m^{-3}$ ) and relatively lower levels in the northern part (within  $35 \mu g m^{-3}$ ) in the BTH, which are aligned with other studies, e.g., Chen et al. (2020) and Zeng et al. (2023).

Comparing the modeled annual average  $PM_{2.5}$  concentrations in the BTH in 2020 with the observations, the simulated  $PM_{2.5}$  values in the BASE simulation in Fig. 2(a) are generally lower, while those in the AFCID simulation in Fig. 2(b) are more consistent with the annual averages obtained from the local observation sites. The difference between the AFCID and BASE simulations in Fig. 2(c) shows that regions with high values are primarily situated in eastern and southern Hebei Province, and the maximum value of AFCID contribution to  $PM_{2.5}$  can reach  $13.5 \mu g m^{-3}$  in the BTH and its neighboring provinces. The addition of the AFCID emissions results in a significant increase in  $PM_{2.5}$  values in 2020 in the BTH, effectively reducing the discrepancy in modeled versus observed values. The correlation coefficients ( $r$ ) between modeled and observed annual average  $PM_{2.5}$  values in the BTH in 2020 are 0.77 for the BASE simulation, and 0.85 for the AFCID simulation. All  $r$  values exhibit statistical significance at the 95 % confidence level, as determined by a two-tailed Student's  $t$ -test.

We further compare the daily mean  $PM_{2.5}$  simulation concentrations

(including AFCID and BASE simulations) with the corresponding observations in the five provinces (Beijing, Tianjin, Hebei, Henan, and Shandong) during 2020 in Fig. 3. The  $r$  values between modeled and observed daily average  $PM_{2.5}$  for five provinces in 2020 are in the range of 0.69–0.78 for the BASE simulation, and in the range of 0.72–0.80 for the AFCID simulation. To ensure a more accurate evaluation of the model's performance in our study, two other parameters are employed: normalized mean bias (NMB) and normalized mean error (NME). The standard ranges for NMB and NME are  $\leq \pm 30\%$  and  $< 50\%$ , respectively, and the goal ranges are  $< \pm 10\%$  and  $< 35\%$  for 24-h mean  $PM_{2.5}$ , where the standards can be regarded as the criterion that is achieved by the majority of models, and the goals should be regarded as the best that the model is anticipated to reach (Emery et al., 2017). In the five provinces, the NMB for daily average  $PM_{2.5}$  concentrations between the BASE simulation and observations ranges from  $-19.04\%$  to  $-27.63\%$ , with the NME ranging from  $33.60\%$  to  $38.39\%$ . For the AFCID simulation, the corresponding NMB values are in the range of  $-4.48\%$  to  $-14.45\%$ , while the NME values are within the range of  $30.27\%$ – $37.23\%$ . The NMB and NME values for daily mean  $PM_{2.5}$  values between the two simulations and observations are generally within standard ranges, with the exception of NMB under the BASE simulation for Tianjin. After the inclusion of AFCID emissions, the model enhances the performance of the  $PM_{2.5}$  simulations by reducing biases in modeled versus observed  $PM_{2.5}$  values, with a decrease in the NMB by  $13.30\%$ – $18.46\%$  and in the NME by  $1.14\%$ – $6.94\%$ . Most NMB and NME values have shifted from the standard ranges to the goal ranges.

Pollutant emissions and meteorological factors may affect  $PM_{2.5}$  concentrations, which thus show evident seasonal differences (Jin et al., 2023; Ma et al., 2023; Peccarrisi et al., 2024). Accordingly, the performance of the GEOS-Chem in simulating  $PM_{2.5}$  under different seasons is evaluated, as well as the influence of AFCID emissions on  $PM_{2.5}$  simulation in different seasons. Fig. 4 displays the scatter plots of modeled and observed daily mean  $PM_{2.5}$  values in the five provinces (Beijing, Tianjin, Hebei, Henan, and Shandong) for the four seasons in 2020, and fitted lines are included as well. During the spring, the  $r$  of the daily average  $PM_{2.5}$  values from the BASE and AFCID simulations and from the observations are between 0.72 and 0.87. In autumn, the corresponding  $r$  values fall within 0.63–0.86, and in winter, the corresponding values are between 0.67 and 0.77. As can be observed from the fitted lines of simulated and observed daily average  $PM_{2.5}$  values, there is a significant underestimation of simulated  $PM_{2.5}$  concentrations in both the BASE and AFCID simulations compared to observations in

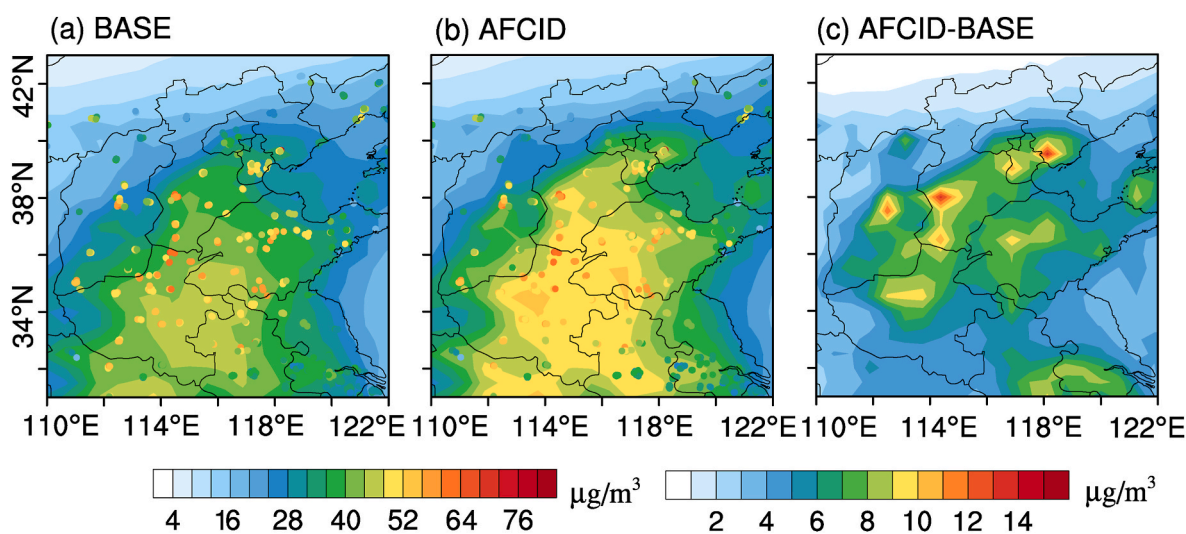


Fig. 2. Distribution of annual average  $PM_{2.5}$  concentrations ( $\mu g m^{-3}$ ) in the BTH and its neighboring regions in 2020 based on (a) BASE simulation by GEOS-Chem, (b) AFCID simulation, and (c) the difference between (a) and (b). The points on the graph are the annual average  $PM_{2.5}$  concentrations in each city observed by CNEMC.

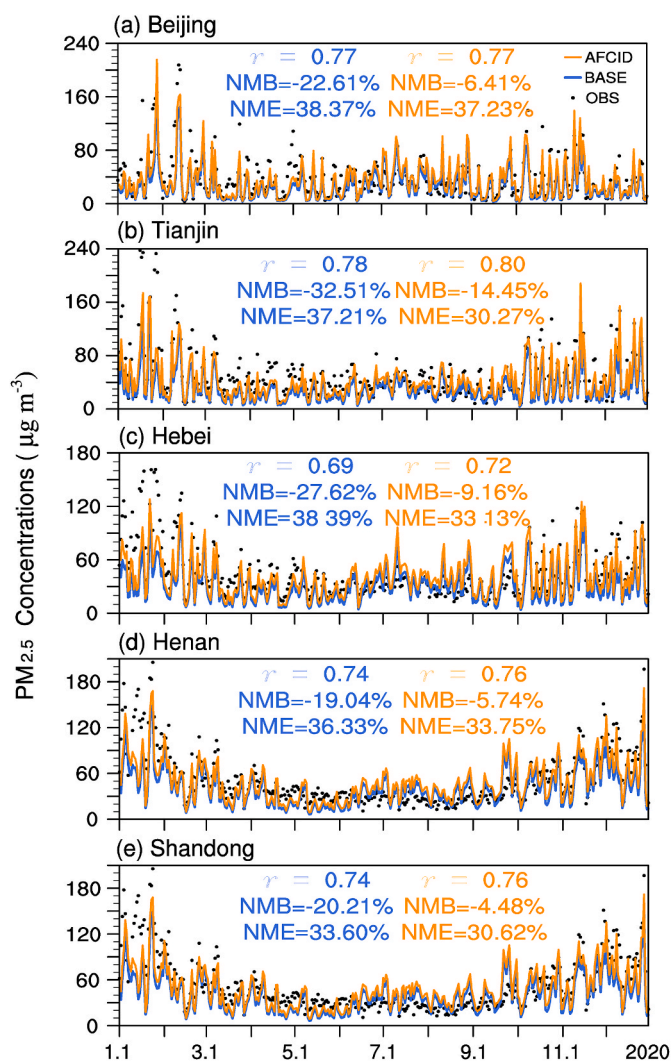


Fig. 3. Simulated (based on BASE and AFCID simulations by GEOS-Chem) and observed daily average  $PM_{2.5}$  concentrations ( $\mu g m^{-3}$ ) in (a) Beijing, (b) Tianjin, (c) Hebei, (d) Henan, and (e) Shandong in 2020, utilizing the Correlation Coefficient ( $r$ ), Normalized Mean Bias (NMB), and Normalized Mean Error (NME) for model validation.

spring, with a similar underestimation noted in winter and autumn. In contrast to other seasons, summer exhibits higher simulated daily average  $PM_{2.5}$  values than those observed. The  $r$  values between the modeled daily average  $PM_{2.5}$  and the observations are ranging from 0.21 to 0.64 in summer, which are significantly lower than those in other seasons. By comparing the orange lines (AFCID simulated-observed fits) and the blue lines (BASE simulated-observed fit) in Fig. 4, it can be observed that the daily average  $PM_{2.5}$  concentrations based on the AFCID simulation provide a better fit to the observations, except during summer. The inclusion of AFCID emissions in spring, fall, and winter improves the biases in modeled versus observed daily average  $PM_{2.5}$  values to some extent and enhances the corresponding  $r$  values.

Previous studies confirm that uncertainties in emission inventories and incomplete model parameterization may impact the model simulation accuracy (Bai et al., 2024; Jang et al., 2022), which could result in potential underestimation or overestimation of  $PM_{2.5}$  concentrations (Wang et al., 2023; Zuo et al., 2023). Qi et al. (2023) found that the GEOS-Chem model showed an underestimation in winter and an overestimation in summer of  $PM_{2.5}$  values compared to the observed concentrations in 2017 in Beijing. In summer, the low  $r$  values between GEOS-Chem modeled and observed  $PM_{2.5}$  have also been found in

some studies, e.g., Jiang et al. (2020) and Zhai et al. (2021), which were 0.45 in East China and 0.53 in North China, respectively. Zhai et al. (2021) further found overestimated nitrate concentrations (by 33 %) during summer in 2016 in the North China, which may originate from the model's overestimation of nighttime nitrate concentrations (Miao et al., 2020). In winter, the model may not perfectly capture the observed peak  $PM_{2.5}$  concentrations, especially during high pollution periods (Dai et al., 2024; Dang and Liao, 2019b). Miao et al. (2020) found that in the winter of 2012 in China, the underestimation of sulfur dioxide emissions led to an underestimated of sulfate concentrations in the GEOS-Chem model. Besides, since most observation sites used in this study are situated in heavily polluted urban environments, where  $PM_{2.5}$  concentrations are relatively high, the model's spatial resolution of  $0.5^\circ \times 0.625^\circ$  may thus not accurately represent the high concentrations at these specific sites, which would potentially introduce some biases into the  $PM_{2.5}$  simulation.

### 3.3. Contribution of AFCID emissions to $PM_{2.5}$ concentrations

In the BTH and its neighboring provinces, the AFCID emissions significantly impact the  $PM_{2.5}$  concentrations. Fig. 5 presents the modeled and observed average  $PM_{2.5}$  values in the five provinces (Beijing, Tianjin, Hebei, Henan, and Shandong) for the four seasons and for the entire year of 2020. It is evident that both the BASE and AFCID simulations underestimate the annual average  $PM_{2.5}$  values compared to the observed values, and the  $PM_{2.5}$  concentrations under the AFCID simulation are closer to the observations. In Beijing, Tianjin, Hebei, Henan, and Shandong, the annual mean  $PM_{2.5}$  values under the BASE simulation are found to be lower than the observed by 8.4, 15.7, 12.4, 9.9, and 9.0  $\mu g m^{-3}$ , respectively; the addition of AFCID emissions cause an increase in simulated annual average  $PM_{2.5}$  concentrations by 6.0  $\mu g m^{-3}$  (17.2 %), 8.8  $\mu g m^{-3}$  (21.1 %), 8.3  $\mu g m^{-3}$  (20.3 %), 6.3  $\mu g m^{-3}$  (20.3 %), and 6.3  $\mu g m^{-3}$  (21.1 %), respectively. Overall, the anthropogenic dust thus has a significant impact on the BTH and its surrounding provinces, with contributions to the annual mean  $PM_{2.5}$  values ranging from 17.2 % to 21.1 %. It is noteworthy that the contribution of AFCID to  $PM_{2.5}$  in Tianjin and Hebei are higher than those in other regions, reaching a peak level of 21.1 %, which is likely related to the intensive industrial activities in the region, especially in eastern and southern Hebei (important industrial centers). The distribution of AFCID emissions in Fig. 1 also confirms this feature, as both cities are located in areas with high values of AFCID emissions.

Moreover, the effect of AFCID emissions on  $PM_{2.5}$  concentrations is evaluated for different seasons. As illustrated in Fig. 5, seasonal mean  $PM_{2.5}$  values under both BASE and AFCID simulations are low during the spring and summer but high during the autumn and winter. The addition of AFCID emissions can increase the modeled seasonal average of  $PM_{2.5}$  by 4.2–12.4  $\mu g m^{-3}$ . Across the five provinces, AFCID emissions contribute significantly to the seasonal average  $PM_{2.5}$  concentrations, which are 4.2–5.3  $\mu g m^{-3}$  (17.6 %–20.6 %) in spring, 6.7–7.3  $\mu g m^{-3}$  (16.1 %–19.5 %) in summer, 6.4–9.7  $\mu g m^{-3}$  (18.8 %–22.8 %) in fall, 6.9–12.4  $\mu g m^{-3}$  (17.1 %–21.2 %) in winter, and 6.5–10.6  $\mu g m^{-3}$  (17.4 %–21.1 %) in heating season. Additionally, with regard to different provinces, AFCID emissions contribute significantly to both seasonal and annual average  $PM_{2.5}$  values in Tianjin and Hebei, but relatively lower in Henan and Shandong.

The contribution of anthropogenic dust to  $PM_{2.5}$  typically shows seasonal variations (e.g., Chen et al., 2023; Gao et al., 2018), often peaking in cold months and reaching its lowest point in summer, as reported in some studies such as Sun et al. (2021) and Wang et al. (2016). This seasonal pattern arises as AFCID emissions are primarily driven by anthropogenic activities including construction, industrial production, and heating. Compared to human activities, meteorological conditions have relatively little impact on anthropogenic dust emission (Chen et al., 2019), and primarily affect its transport and deposition (Du et al., 2023). However, our research shows a different phenomenon,

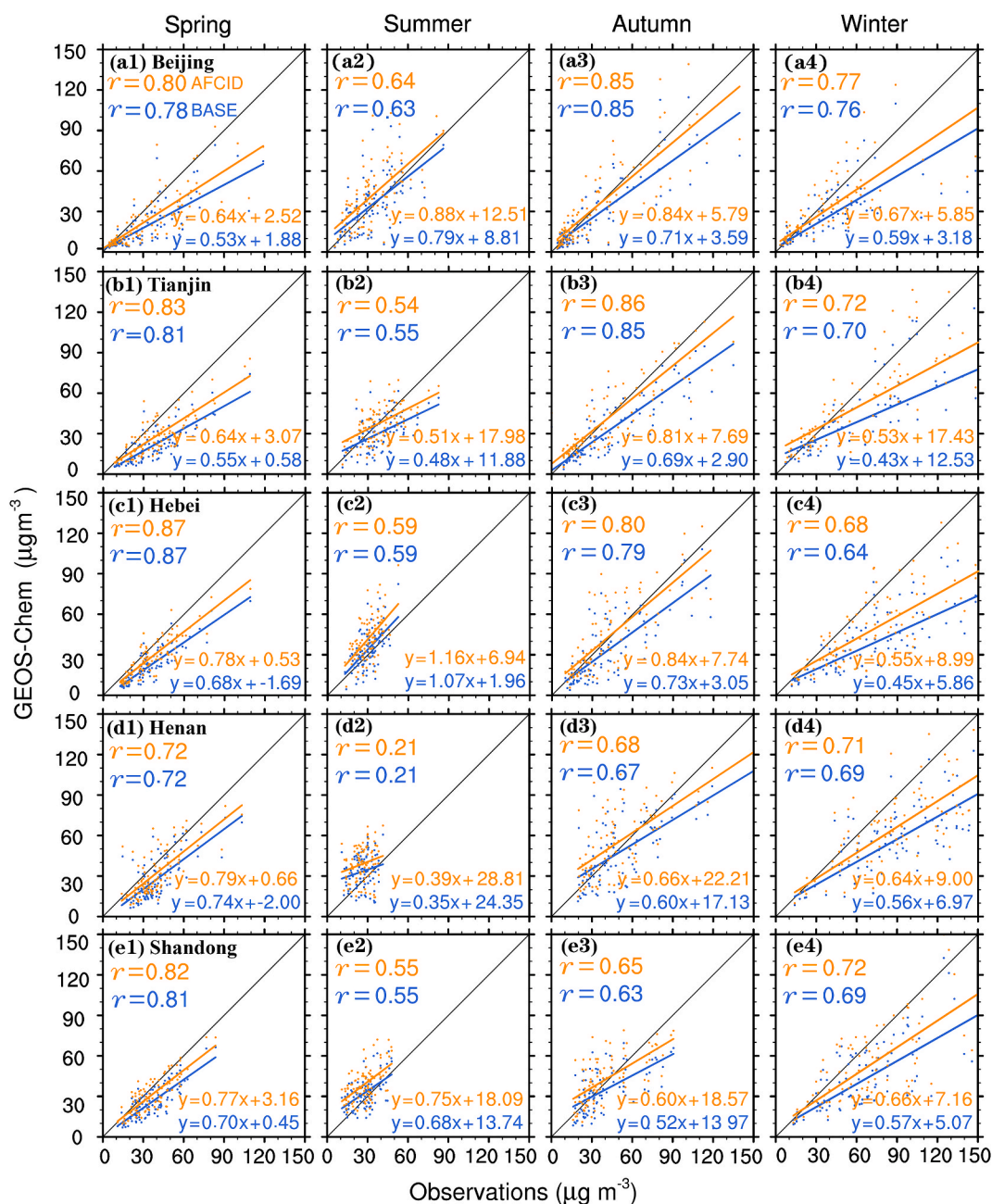


Fig. 4. Scatter plots of simulated (based on BASE and AFCID simulations by GEOS-Chem) and observed daily average PM<sub>2.5</sub> concentrations (μg m<sup>-3</sup>) in four seasons of 2020 for (a1-a4) Beijing, (b1-b4) Tianjin, (c1-c4) Hebei, (d1-d4) Henan, and (e1-e4) Shandong. Correlation Coefficient (r) and linear equations of the fit lines for both simulated and observed scatter points are included.

with anthropogenic dust contributing a higher proportion to the total PM<sub>2.5</sub> in the summer than in the spring in 2020. This discrepancy may be partially explained by the exceptional circumstances of the COVID-19 pandemic. Lockdown restrictions in early 2020 (January–March) drastically suppressed normal springtime human activities and associated dust emissions; in contrast, summer activities, while potentially still affected, operated closer to normal levels (Zheng et al., 2021). Consequently, simulated anthropogenic dust exhibited enhanced relative contributions in summer compared to the suppressed spring period.

### 3.4. Impact of AFCID emissions on PM<sub>2.5</sub>-Related premature mortality

To investigate the effects of AFCID emissions on PM<sub>2.5</sub>-related mortality in the five provinces (Beijing, Tianjin, Hebei, Henan, and Shandong), the outcomes of PM<sub>2.5</sub>-related mortality derived from two

sensitivity tests (BASE simulation and AFCID simulation) are analyzed and compared. The GEMM 5-COD model and the IER model include five diseases: LRI, COPD, LC, IHD, and stroke. Fig. 6 shows the number of PM<sub>2.5</sub>-related mortality in the five provinces in 2020, based on the BASE and AFCID simulations. The results of both the GEMM 5-COD model and the IER model show that among the five diseases, IHD and stroke are the two with the highest number of PM<sub>2.5</sub>-related mortality, while the lowest mortality is observed in LRI cases, which is consistent with some studies conducted in China e.g., Dang and Liao (2019a) and Wang et al. (2021).

In the five provinces, the numbers of PM<sub>2.5</sub>-attributable mortality under the AFCID simulation in 2020, calculated by the GEMM 5-COD model/the IER model, are 37.3/28.2 thousand, 25.5/19.1 thousand, 125.5/94.1 thousand, 173.4/127.6 thousand, and 178.1/137.1 thousand. Among them, the numbers of additional PM<sub>2.5</sub>-related premature

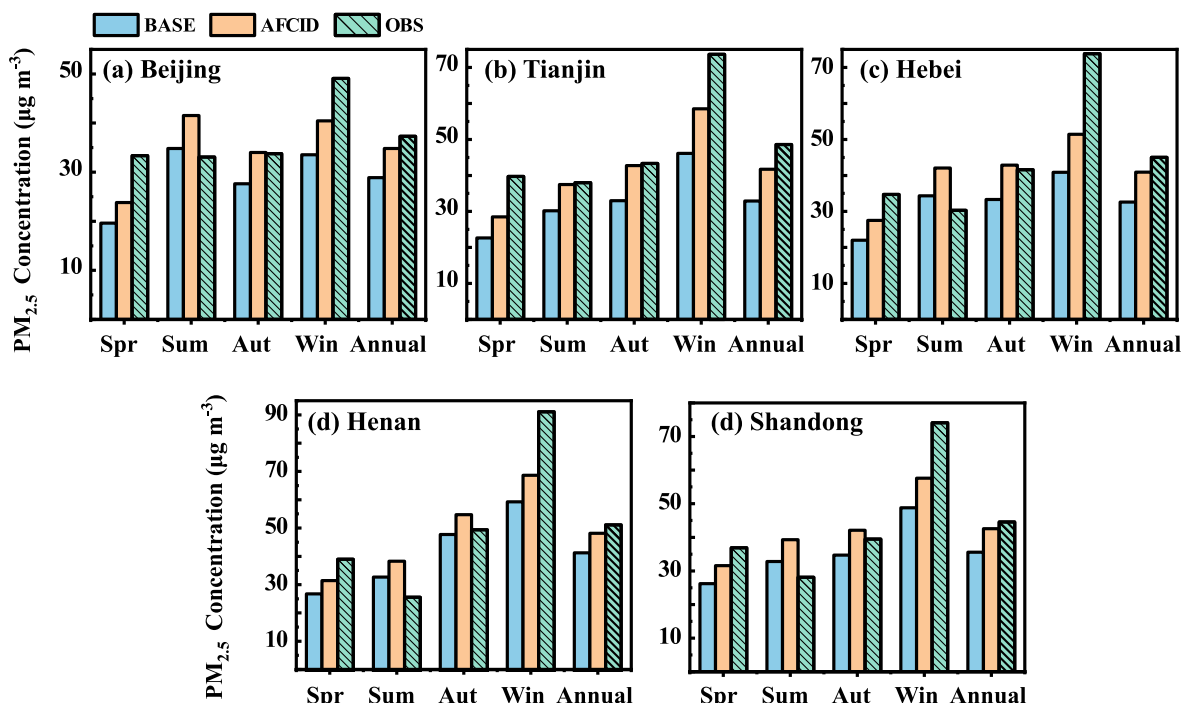


Fig. 5. Seasonal and annual average concentrations of PM<sub>2.5</sub> (µg m<sup>-3</sup>) in 2020 for (a) Beijing, (b) Tianjin, (c) Hebei, (d) Henan, and (e) Shandong, based on BASE and AFCID simulations by GEOS-Chem and CNEMC observational data.

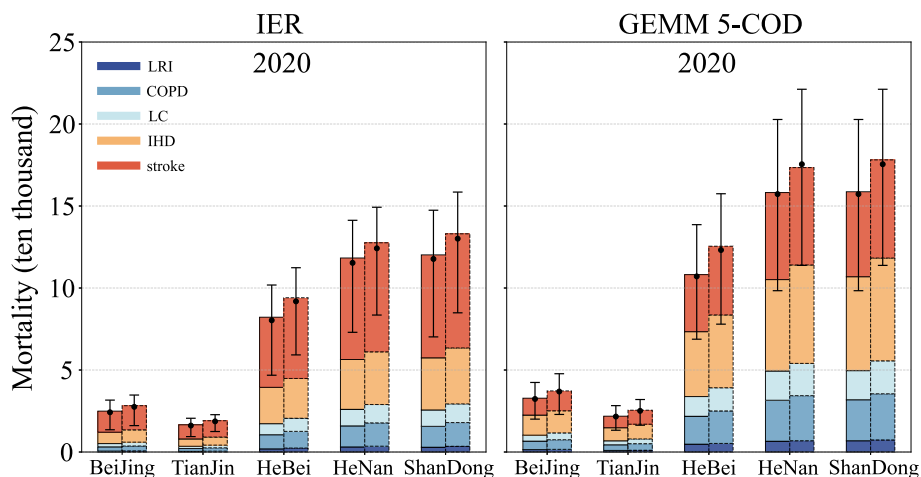


Fig. 6. Premature deaths (due to five diseases: lower respiratory infections (LRD), chronic obstructive pulmonary disease (COPD), lung cancer (LC), ischaemic heart disease (IHD), and stroke) attributed to PM<sub>2.5</sub> exposure in 2020 for the five provinces (Beijing, Tianjin, Hebei, Henan, and Shandong). Calculations are based on the IER model (left panel) and the GEMM 5-COD model (right panel), using annual average PM<sub>2.5</sub> concentrations simulated by GEOS-Chem. Error bars represent the 95 % confidence intervals from 1000 Monte Carlo simulations, with dots indicating the mean estimates.

deaths due to AFCID emissions are 4.5 thousand (11.9 %)/3.3 thousand (11.7 %), 3.6 thousand (14.3 %)/2.5 thousand (13.0 %), 17.3 thousand (13.8 %)/11.9 thousand (12.6 %), 15.2 thousand (8.8 %)/9.3 thousand (7.3 %), and 19.4 thousand (10.9 %)/12.8 thousand (9.6 %), respectively, in each province in 2020.

It has been noted that there are some differences in the estimation of PM<sub>2.5</sub>-related mortality (Burnett et al., 2018; Li et al., 2018; Zhang et al., 2017). Maji et al. (2018) pointed out significant differences in the estimation of annual deaths attributed to PM<sub>2.5</sub> in China, with figures ranging between 1.2 million to 1.7 million in 2015. Liu et al. (2022) pointed out that using different PM<sub>2.5</sub> datasets, the number of PM<sub>2.5</sub>-related deaths ranged from 1.39 to 1.56 million in eastern China in 2016. The differences may arise from the use of varied methodology and risk exposure models (Fang et al., 2016; Guan et al., 2019), as well

as uncertainty in the estimation of PM<sub>2.5</sub> values (Liu et al., 2022). For example, Wan et al. (2024) employed the Fusion relative risk model to assess the numbers of PM<sub>2.5</sub>-related mortality in China during 2020, including six diseases (LRI, COPD, LC, IHD, stroke and Type 2 Diabetes), and found that the numbers of premature deaths in the five provinces of Beijing, Tianjin, Hebei, Henan and Shandong were approximately 58 thousand, 38 thousand, 168 thousand, 206 thousand and 210 thousand, respectively, which were higher than our findings. This difference may be attributed to the inclusion of Type 2 Diabetes in their study, as well as the higher total premature deaths calculated by the Fusion model compared to the GEMM-5COD model.

Additionally, there are some uncertainties in our assessment, including limitations in PM<sub>2.5</sub> simulations and health impact evaluation. Firstly, the PM<sub>2.5</sub> simulations at a coarse resolution may introduce

errors, especially in urban areas. The relatively large grid scale may not adequately capture fine-scale variations in pollution within cities, which could cause an underestimation of peak PM<sub>2.5</sub> values in highly polluted areas. The health risks for populations exposed to the high pollution levels thus might be underestimated, potentially weakening the assessment of risks for the vulnerable groups. Secondly, our health impact assessment relies only on the PM<sub>2.5</sub> mass concentrations, which likely underestimates the health burden by failing to capture the composition-specific toxicity. As evidenced by Xiao et al. (2023), in industrial northwest China, PM<sub>2.5</sub> (including sources contributing to AFCID like coal combustion, cement dust, and industrial activities) contained elevated levels of heavy metals (e.g., chromium at 3times of background values), which were linked to greater health risks per unit mass than generic PM<sub>2.5</sub>. As previously mentioned, the eastern and southern regions of Hebei province are significant industrial centers, with higher AFCID contributions to PM<sub>2.5</sub>. The health impacts in these regions are likely to be greatly underestimated.

#### 4. Conclusions

This study quantified the impact of anthropogenic dust (AFCID) emissions on PM<sub>2.5</sub> concentrations and associated public health in the BTH and its neighboring provinces (Henan, Shandong). The China regional AFCID emission inventory was updated to 2020 based on Philip et al. (2017), which significantly improved the GEOS-Chem model performance. AFCID emissions were a major contributor to PM<sub>2.5</sub> pollution, elevating annual average concentrations by 6.0–8.8 μg m<sup>-3</sup> (17.2%–21.1%) in the study region in 2020, and seasonal concentrations by 4.2–12.4 μg m<sup>-3</sup> (17.1%–22.8%). Calculated by GEMM 5-COD model/IER model, AFCID emissions were found to be a significant contributor to PM<sub>2.5</sub>-related premature deaths with 3.6 thousand to 19.4 thousand (8.8%–14.3%)/2.5 thousand to 12.8 thousand (7.3%–13.0%) in the five provinces.

This study provides a quantitative basis for understanding AFCID impacts and offers valuable information for addressing PM<sub>2.5</sub> pollution, developing effective emission reduction strategies, and protecting public health in the region. However, uncertainties remain, particularly in AFCID emission estimation (e.g., uncertainties in MEIC emission inventories, lack of long-term continuous observations to quantify emissions), PM<sub>2.5</sub> simulation (coarse model resolution, imperfect physicochemical mechanisms in models), and health effect calculation (e.g., dependence on PM<sub>2.5</sub> concentration datasets and exposure-response models).

#### CRedit authorship contribution statement

**Juan Lv:** Writing – original draft, Visualization, Investigation, Data curation. **Yu-Hao Mao:** Writing – review & editing, Methodology, Conceptualization. **Hong Liao:** Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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