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Source Contributions to PM2.5 in Three Megacities of Beijing, Tianjin and Shanghai in China

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Abstract. This study quantifies the source contributions to PM2.5 in three major Chinese cities of Beijing, Tianjin, and Shanghai during the period of June to August 2016. The sensitivity analysis is employed by individually eliminating each sector to identify their respective contributions. The numerical simulations reveal that industry is the dominant contributor to PM2.5 pollution in all three cities with contributions ranging from 41.01% to 53.42%. The contributions of residential-commercial, energy and transportation are in the range of 11.25% to 27.21%, 17.45% to 20.61%, and 5.89% to 15.02%, respectively. Agriculture and deforestation-wildfire are found to contribute 4.23% to 7.28% and 2.60% to 5.30%, respectively.

Keywords. PM2.5, source contributions, urban air

1. Introduction

The global phenomenon of urbanization and population growth has led to a significant increase in anthropogenic pollution, which has become a major cause of environmental issues. In recent years, excessive discharge of emissions such as sulfur dioxide, fossil fuels, and gas-phase photochemical compounds have caused environmental issues like acid rain, the greenhouse effect, and ozone depletion. As a result, air pollution has become a critical topic, prompting in-depth discussions about environmental issues from the perspective of chemical components [1-7]. To mitigate the impact of pollution, it is crucial to comprehend the pollutant diffusion process and accurately determine the contribution of pollutant sources.

Among the atmospheric pollutants, PM2.5 is a class of particles with a diameter less than or equal to 2.5 μm that significantly affects air quality and visibility [8-10]. These particles have the capacity to easily transport toxic and hazardous substances [11], persist in the atmosphere for extended periods, and travel significant distances, making them a significant threat to human health and atmospheric environment quality [12, 13]. In March 2012, the Chinese government made amendments to the air quality assessment criteria by including PM2.5 in the monitoring of air quality [14].

For carrying out source apportionment studies, chemical transport models are powerful tools commonly used [15, 16]. In this study, we utilize WRF-Chem (Weather

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Research and Forecasting model with Chemistry) model, developed by National Center for Atmospheric Research (NCAR), PNNL (Pacific Northwest National Laboratory), and NOAA (National Oceanic and Atmospheric Administration). WRF-Chem allows for simultaneous modeling of chemical transformation and transportation of trace gases with meteorology, enabling two-way coupling and online feedback between the meteorological model and the chemical transport model. Currently, WRF-Chem is one of the fastest and most promising air quality models.

This study focuses on three major Chinese cities of Beijing, Tianjin, and Shanghai, which are facing serious air pollution issues. We aim to quantitatively analyze the contributions of different emission sources to PM2.5 pollution, using the WRF-Chem model simulation. The sectors considered in this study are agriculture, deforestation-wildfire, energy, industry, residential-commercial, and transportation. Firstly, a numerical simulation is conducted for the period of June to August 2016, and the results are validated by comparison with observations. Next, sensitivity and control experiments are performed to identify and quantify the respective contributions of each sector to PM2.5 pollution.

The paper is organized as follows. Section 2 provides an overview of the methodology used in this study. Section 3 presents the numerical results and discussions based on the analysis of the source contributions of PM2.5 in the three Chinese megacities. Finally, Section 4 summarizes the main findings and draws conclusions based on the results obtained.

2. Methodology

2.1. Model Configurations and Input

The WRF-Chem model (version 3.1, http://www2.mmm.ucar.edu/wrf/users/) is employed in this study. The selected area encompasses a size of 1800 km × 1800 km, with its center located at (117°E, 37°N). This region includes the three major cities of Beijing, Tianjin, and Shanghai. In recent years, these cities have faced significant challenges of air pollution resulting from rapid urbanization and industrialization. Therefore, the study of PM2.5 pollution in these areas has important scientific and practical significance, and can provide valuable information for the development of effective air pollution control strategies.

The simulation in this study adopts a spatial resolution of 50 km × 50 km and utilizes 30 vertical layers, spanning from the surface to the 100-hPa level, which corresponds to approximately 20 km. The vertical grid spacing varies from 60 m near the ground to 1.5 km near the uppermost region of the area. The same grid configuration is used for calculating the meteorological information.

The parameterization schemes used are listed in Table 1. The chemical mechanism used for the study is RADM2 with MADE/SORGAM aerosols. The Fast-J photolysis scheme is utilized for photolysis calculations and is coupled with hydrometeors, aerosols, and convective parameterizations. Anthropogenic emissions data is obtained from PKU Inventory (http://inventory.pku.edu.cn), which includes 27 components such as PM2.5, PM10, SO_2, NO_x, CO, TSP, ACE, ACY, ANT, BaA, BaP, BbF, BC, BghiP, BkF, CH_4, CHR, CO_2, DahA, FLA, FLO, IcdP, NAP, NH_3, OC, PHE and PYR, along with 6 sectors of agriculture, deforestation-wildfire, energy, industry, residential-commercial, and transportation. The monthly emission inventory used has a resolution of 0.1° × 0.1°.

Additionally, the National Center for Environmental Prediction Final Operational Global Analysis data (http://rda.ucar.edu) on 1-degree by 1-degree grids with a temporal resolution of six hours is utilized to prepare for simulations, including meteorological initial and boundary conditions.

Table 1. Parameterization scheme used in WRF-Chem simulation.

Chemical options	Description
Biogenic emissions	Online calculation of biogenic emissions [17, 18]
Anthropogenic emissions	RADM2/MADE/SORGAM anthropogenic emissions
Gas-phase chemical mechanism	RADM2 [19-21]
Photolysis scheme	Fast-J photolysis
Aerosol scheme	MADE/SORGAM [19, 22]

The simulation period ranges from 0000UTC on 1 June 2016 to 1600UTC on 30 August 2016, with the first 9 days being considered a spin-up period [23]. In order to assess the accuracy of the simulation, the PM2.5 mass concentration measurements collected from air quality stations operated by the Chinese Ministry of Environmental Protection within the studied area are used for validation purposes.

2.2. Performance Evaluation for the Model Simulation

To conduct numerical simulations for sensitivity analysis, a base case simulation is first performed, including all six major sectors of emission. The results are verified against observed values. Once the results of the base case simulation are evaluated, PM2.5 mass concentrations are simulated with one of the six major sectors excluded, to observe the source contribution of the excluded sector. The source contribution is then expressed as a percentage of the PM2.5 mass concentration decrease when the sector is removed and computed as

$$\text{Con} = \frac{S_{total} - S_{exclude}}{S_{total}} \tag{1}$$

where Con represents the contribution of a sector, S_{total} represents the results of base case simulation with all six major sectors included, $S_{exclude}$ represents the simulation results obtained by removing the sector of interest from the total emission.

3. Results and Discussions

3.1. Simulation Including all Sectors

In this simulation, all six sectors are included in the emission configuration. Figure 1 illustrates the daily average concentrations of PM2.5 in three cities studied in this paper, as simulated by WRF-Chem and observed. The findings reveal a substantial alignment between the simulated pollutant concentrations and the observed values, with a strong correlation observed between them. Specifically, the correlation coefficient (R) exceeds 0.5, indicating a significant correlation between the two, and the p-value is well below 0.05, further indicating a significant correlation.

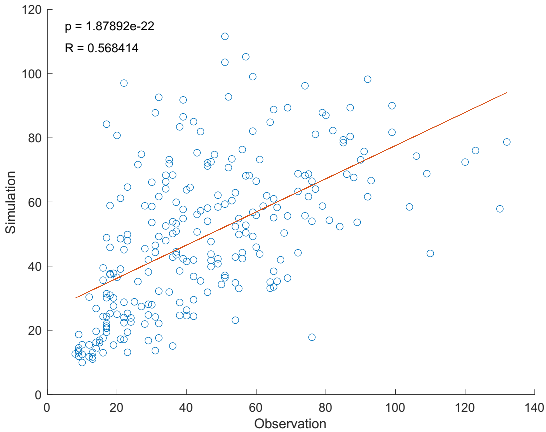

Figure 1. Comparison of simulated daily averaged PM2.5 concentrations from 10 June to 30 August 2016 with the observation in three cities.

Figure 2 presents the comparison between the simulated and observed time series of PM2.5 mass concentration in the three cities. The model generally reproduces the diurnal variation of PM2.5 mass concentration well. Meanwhile, Figure 3 displays the spatial distribution of the average surface concentrations, as simulated, during the period of June 10 to August 30, 2016. The findings suggest a notable increase in PM2.5 mass concentrations in Beijing, Tianjin, and Shanghai during the specified period. The urban characteristics of these cities might be the main reason for this phenomenon, with Beijing being China's administrative center, Shanghai its economic center, and Tianjin is the largest port in northern China.

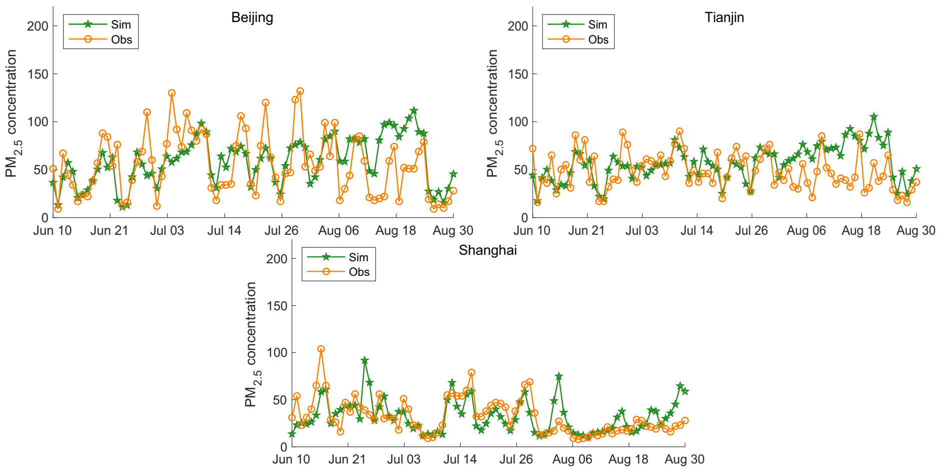

Figure 2. Comparisons of time series of simulated and observed daily average PM2.5 mass concentration in the cities.

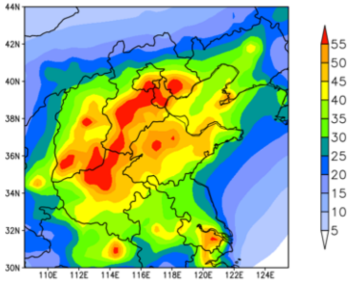

Figure 3. The spatial distribution of simulated averaged surface concentrations from 10 June to 30 August 2016.

3.2. Simulation Excluding Agriculture

The influence of agriculture on PM2.5 pollution is mainly reflected in the agricultural sector, especially in livestock rearing and fertilizer application that emits ammonia [24].

Figures 4a-4c present a comparison of the simulated time series of PM2.5 mass concentration, including all sectors and excluding agriculture, in the three cities. Based on the results, the average contribution of agriculture to PM2.5 emissions during the study period can be calculated (as equation (1)). For the three cities studied, namely Beijing, Tianjin, and Shanghai, the agricultural contributions are 4.23%, 4.53%, and 7.28%, respectively.

3.3. Simulation Excluding Deforestation-Wildfire

Forests play a crucial role in mitigating air pollution by blocking the process of air pollutant propagation and improving environmental quality through the structure and function of trees. This helps maintain human health by decreasing exposure to harmful pollutants. However, current issues, such as deforestation and forest wildfires, pose a serious threat to the ecological balance, contributing to the continuous pollution of air pollutants, including PM2.5. Additionally, forest wildfires also produce particulate pollutants that further worsen air quality.

Figures 4d-4f present a comparative analysis of the simulated time series of PM2.5 mass concentration, including both the base case with all emission sectors and the deforestation-wildfire excluded case. Based on the results, the contributions of deforestation-wildfire to PM2.5 can be computed, which are 2.85%, 2.60%, and 5.30% for the cities of Beijing, Tianjin, and Shanghai, respectively.

3.4. Simulation Excluding Energy

When it comes to the energy industry, fossil energy is often the primary consideration. Nevertheless, it should be noted that the combustion of fossil fuels is a significant contributor to PM2.5 emissions. Figures 4g-4i illustrate the simulated time series of PM2.5 mass concentration of base case results in 3.1 and results with emissions that exclude the energy sector. By examining the results in Figures 4g-4i, we can compute the average contribution of energy to PM2.5 in the three cities of Beijing, Tianjin, and Shanghai, which are 20.61%, 17.45%, and 19.44%, respectively. These data suggest that PM2.5 pollution resulting from energy usage was severe during the period from June

2016 to August 2016, with Beijing exhibiting a greater impact in this regard than the other two cities.

Figure 4. Comparisons of time series of simulated daily average PM2.5 mass concentration including total sectors and excluding agriculture: (a)-(c) deforestation-wildfire; (d)-(f) energy; (g)-(i) industry; (j)-(l) residential-commercial; (m)-(o) transportation (p)-(r) respectively in the cities.

3.5. Simulation Excluding Industry

The cities under study in this research are predominantly located in heavily industrialized regions. Industrial activities not only emit primary pollutants such as dust, soot, and sulfur dioxide directly into the environment, but also generate secondary pollutants through chemical reactions involving nitrogen oxides, volatile organic compounds, and other emissions.

Figures 4j-4l compare the simulated time series of PM2.5 mass concentration of results from including all sectors and excluding industry. Based on the result, we calculated the average contribution of industry to PM2.5 emissions during the studied period, which are 41.01%, 49.97%, and 53.42% for Beijing, Tianjin, and Shanghai, respectively. These findings indicate that the three cities are highly industrialized, and industrial activities are the primary source of PM2.5 pollution among the six sectors, which is consistent with the characteristics of urban areas.

3.6. Simulation Excluding Residential-Commercial

Commercial and residential areas are ubiquitous in our daily lives. For most people, cooking in the kitchen is the activity that exposes them the most to PM2.5. During the cooking process, the high temperatures cause thermal decomposition or cracking of edible oils and foods, producing a mixture of gaseous, liquid, and solid particles, which are commonly referred to as soot.

Figures 4m-4o compare the simulated time series of PM2.5 mass concentration between the case including total sectors and the case excluding residential-commercial. The average contribution of residential-commercial to PM2.5 emissions during the time studied is computed. For the three cities studied which are Beijing, Tianjin, and Shanghai, the contributions of residential-commercial are 27.21%, 21.61%, and 11.25% respectively.

3.7. Simulation Excluding Transportation

Over the past decade, transportation has been identified as a significant source of PM2.5, with automobile exhaust and road dust being the primary contributors. This underscores the need for more environmentally friendly modes of transportation and stricter regulations to reduce emissions from vehicles and improve air quality in urban areas.

Figures 4p-4r compare the simulated time series of PM2.5 mass concentration between the base case that includes all sectors and the case that excludes transportation. The average contribution of transportation to PM2.5 emissions during the study period in Beijing, Tianjin, and Shanghai was found to be 6.32%, 5.89%, and 15.02%, respectively. These findings indicate that transportation emissions play a relatively minor role in PM2.5 pollution in Beijing and Tianjin, but are a major contributor in Shanghai.

4. Discussion and Conclusions

The primary objective of this study is to determine the contribution of various sectors to PM2.5 pollution in three Chinese cities of Beijing, Tianjin, and Shanghai, during the period from June to August 2016 using the WRF-Chem model. The sectors studied include agriculture, deforestation-wildfire, energy, industry, residential-commercial, and transportation.

The results of the simulation indicated that industry, residential-commercial, energy, transportation, agriculture, and deforestation-wildfire contributed to PM2.5 pollution in the range of 41.01% to 53.42%, 11.25% to 27.21%, 17.45% to 20.61%, 5.89% to 15.02%, 4.23% to 7.28%, and 2.60% to 5.30%, respectively, in the three studied cities. Although the order of contributions from high to low was generally consistent, there were some variations in individual cases. For instance, in Shanghai, the order was industry, energy, transportation, residential-commercial, agriculture, and deforestation-wildfire.

The current study only explored the source contribution of each sector to PM2.5 pollution in the selected cities and did not explore the potential interactions between different regions in more detail. Further research is needed to investigate this issue to gain a better understanding. Therefore, it is essential to conduct more detailed studies to shed more light on the underlying mechanisms of PM2.5 pollution.

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