Regional PM$_{2.5}$ Estimation in Beijing Based on WRF-Chem Model

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Abstract. Air pollution remains to be a challenge for the government and scholars, especially the particulate matter (PM$_{2.5}$), resulting in many casualties and huge economic losses. It is imperative to understand the distribution characteristics of PM$_{2.5}$ and analyse some influencing factors including the wind speed, humidity and atmospheric boundary conditions. A certain scholars have studied the relationship between the PM$_{2.5}$ and the atmospheric boundary condition. However, there is no study about the correlation analysis between the PM$_{2.5}$ and wind speed or humidity. Considering all components in the atmosphere affecting each other and the ability of WRF-Chem simulating all of the atmospheric parameters, we utilized the WRF-Chem to simulate the wind speed, humidity and PM$_{2.5}$. Then firstly the PM$_{2.5}$ simulated from WRF-Chem are validated with those at the ground stations to evaluate the reliability of WRF-Chem. Secondly, the correlation analysis between the PM$_{2.5}$ and wind speed or humidity was done, with the correlation coefficient -0.7 and 0.48 in January, 2019. And the results demonstrate that the wind is helpful to decrease the serious air pollution in winter while the humidity has a little effect on the elimination of the particulate matter. The WRF-Chem is potential and an effective tool for the study of the air pollution.

1. Introduction

With the rapid economic growth in China in the recent decades, the problem of air pollution is becoming more and more serious. Although this has attracted the attention of the society and the government, and some relevant control measures have been taken but the problem of air pollution has not been completely solved.

Among all, fine particulate matter (PM$_{2.5}$) has become the most important air pollutant in China after the release of the new environmental protection standard (environmental air quality standard GB3095-2012). Chemical element composition analysis of PM shows that harmful and heavy metal elements from coal burning, fuel oil and industrial pollution are enriched by tens to tens of thousands of times in PM$_{2.5}$. Therefore, PM$_{2.5}$ and other fine particulate matter are of great harm to human health. And it is imperative to strengthen the formulation of pollution prevention and control measures through the dynamic study of its concentration spatial distribution and trend of change.

For air pollution control, it is necessary to consider the continuous spatial and temporal distribution of pollutant concentration on the basis of understanding the temporal distribution characteristics of pollutant concentration at a single site. The Weather Research&Forecast (WRF) model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. For researchers, WRF can produce simulations based on actual atmospheric conditions (i.e., from observations and analyses) or idealized conditions. WRF also
can offer operational forecasting a flexible and computationally-efficient platform and so is potential to simulate all of the atmospheric parameters, including temperature, water vapor and humidity and so on. And the WRF-Chem model is one of its functions and can be used to simulate the spatial distribution of PM$_{2.5}$ and understand its spatial variation rule [1]. In addition, WRF-Chem can use online coupling technology to simulate more continuous temporal pollutant data and compensate the loss of atmospheric information caused by long time interval, so as to simulate air quality with high time resolution [2].

In recent years, scholars have done some researches on the WRF-Chem simulated atmospheric pollution. Yang Guangying et al [3] evaluated the forecast PM$_{2.5}$ in Anhui province, Zhou GuangQiang et al [4] evaluated ozone in Shanghai and PM$_{2.5}$ in east China, and the studies drew the conclusion that the WRF-Chem model could be used to provide accurate prediction of air pollutants in the study area. The comparative study results of Greel er al. [2] Also show that WRF-Chem has excellent prediction effect on PM$_{2.5}$ and ozone. Some other scholars have conducted studies on the integrated meteorological model: Zhang Hanyu et al. Fused WRF and CAMx model to simulate PM$_{2.5}$ in Beijing-Tianjin-Heibei region [5]. However, most studies only analyze the temporal and spatial distribution characteristics and transport mechanism of PM$_{2.5}$ of different scales, without analysis of its relationship with various relevant meteorological elements and corresponding explanations. As is known to all, man-made emission sources and regional transport are the main causes of the pollution [5] [6]. In addition, the formation and evolution of aerosols are also closely related to local meteorological conditions [7-9]. The spatial-temporal continuum of meteorological elements simulated by WRF-Chem provides the factors that may explain the evolution of PM$_{2.5}$ over small scales.

Serious and long-lasting air pollution often occurs in Beijing in recent years [10]. Combined with the monitored data of PM$_{2.5}$ at ground stations, this study utilized WRF-Chem model to simulate PM$_{2.5}$ concentration in Beijing and its surrounding areas, evaluated its accuracy, and analyzed the relationship between the PM$_{2.5}$ modeled by WRF-Chem and its relevant meteorologically influencing factors such as humidity and ground wind speed.

2. Materials and methods

2.1. Study area

Beijing is located in north China, with its center at 116° 20′ E and 39° 56′ N and has a total area of 16410m$^2$. Mountains surround the west, north and northeast of Beijing, and the southeast is a plain that slopes gently toward the Bohai. Compared with other areas, Beijing has a dry climate, therefore serious and long-lasting air pollution often occurs in Beijing in recent years, especially in winter [11]. Figure 1 shows the digital elevation model (DEM) and the distribution of the PM measurement stations, where the PM$_{2.5}$ values were obtained.

![Figure 1. Beijing DEM and PM sites distribution](image-url)
2.2. Data collection
Ground PM$_{2.5}$ concentration data were acquired from field collection (see Figure1) and Beijing environmental monitoring center and were used to evaluate the accuracy of the WRF-Chem simulated characteristics of PM2.5 during November 20, 2014 solstice 22. The PM monitoring sites were evenly distributed throughout the study area according to the longitude. The final (FNL) operational global analysis data from the Global Forecast System (GFS) were downloaded at the official website of the National Centers for Environmental Prediction (NCEP) (https://rda.ucar.edu/) and were regarded as the initial and boundary conditions as the WRF-Chem model input. Chemical emission inventory is an important part of air quality numerical research and prediction and a number of emission inventories with different resolutions have been developed. Data on chemical emission sources were obtained from the official website (ftp://aftp.fsl.noaa.gov/divisions/taq/global_emissions/). In this study, the meteorological data simulated from WRF-Chem model were used as meteorological sounding data to study the possible correlation between meteorology and haze pollution.

2.3. Model configuration
WRF-Chem mode is a regional chemical/transport mode that is completely coupled in time and space and truly transmitted online by NOAA, NCAR and other units on the basis of WRF mode [2]. WRF-Chem encompasses an entirely new approach to atmospheric chemistry. Its chemical and meteorological processes use the same horizontal and vertical coordinate systems, the same physical parameterization scheme, it has no interpolation in time, and it can take into account the feedback effect of chemistry on the meteorological processes (WRF-Chem Version 3.9.1.1 User`s Guide).

In this study, simulations were conducted during November 20, 2014 solstice 22 and January 25, 2019 solstice 27. The first time period was used to test the accuracy of the model while the second time frame is used for the prediction of the PM$_{2.5}$ resolution in January 25, 2020 solstice 27. The modeling domain was made up of a three-level nested domain, with a spatial resolution of 9 km for domain 1 (D1), 3 km for domain 2 (D2) and 1 km for domain 3 (D3). The center of the nested domain is 116° E, 40° N.

The biological emissions were computed online by the MEGAN module, ISORROPIA dynamic equilibrium aerosol mechanism was adopted for inorganic aerosols, and SORGA was adopted for secondary organic aerosols [12]. Physical schemes include WSM3-class micro-physics scheme, Kain Fritsch (KF) cumulus scheme and Unified Noah land plan, etc. The meteorological time step is 30s, and the forecast time is 48 hours.

Furthermore, the wind speed and the precipitable water vapor was extracted from the WRF out files and some related calculation were carried out to further investigate the correlation between the formation and evolution of the haze and the forecast meteorological parameters during January 25, 2019 solstice 27.

3. Results and discussion
3.1. Model evaluation
We used the mean absolute deviation (MAE) as statistical parameters to evaluate the accuracy of the WRF model. Eight sites were selected from our study domain and the simulated data were compared with the observed data.
Figure 2. The plot to compare the PM2.5 between simulated from WRF-Chem and ground station sites. The blue line is the WRF-Chem and the red line is for the ground sites data.

Figure 2 shows the concentration of PM$_{2.5}$ from the WRF-Chem model and monitoring sites. The mean absolute deviation (MAE) is 0.94 µg/m$^3$, suggesting that simulations were well reproduced based on the WRF model. The result showed that the WRF-Chem simulated data are able to represent the true values, especially that of heavy pollutant. It is considered effective for the following analysis.

3.2. Meteorological conditions

Meteorological conditions have a significant effect on the formation and dissipation of hazardous pollution [13]. To quantitatively explore the impact of some meteorological factors on surface PM$_{2.5}$ concentration, the analysis was conducted during the winter of 2019 since winter is the peak season for particulate matters. The correlation between it and wind speed and precipitable water vapor (PWV) were evaluated.

The PWV refers to the total amount of water vapor contained in a column of air unit face value, and is a quantitative from of humidity. High humidity promotes the growth of hygroscopic particles and affects the generation and transformation of pollution particles [14].

Figure 3. The spatial distribution of PM$_{2.5}$ (left), PWV (middle) and wind speed (right)

Figure 3 shows the spatial distribution characteristics of the concentration of PM$_{2.5}$, PWV and wind speed. As we can see, the PM$_{2.5}$ concentration is positively correlated with PWV during the research period, with the correlation coefficient of 0.48. However, the wind speed is negatively correlated with the PM$_{2.5}$ concentration, demonstrating that the stronger wind is highly beneficial for helping to reduce air pollutions. However, it is worth noting that the wind cannot eliminate the air pollution, the pollution could be just transformed from one place to another.
4. Conclusions
Solving the air pollution is important to the human health and social development. This study firstly validated the PM$_{2.5}$ simulated from WRF on November 20, 2014 solstice 22 and January 25, then analyzed the spatial-temporal distribution of PM$_{2.5}$ and its correlated meteorological factors with WRF model from January 25, 2019 solstice 27. The simulated results were an average of 30 minutes. The main conclusions are summarized as follows.

The mean absolute deviation (MAE) between the WRF simulated and observed PM$_{2.5}$ is 0.94 μg/m$^3$ suggesting that simulations were well reproduced based on the WRF model. And we can conclude that the WRF-Chem model is capable to accurately simulate the temporal and spatial distribution characteristics of PM$_{2.5}$ in Beijing. It provides new insights for researchers into the way we study the atmospheric parameters, especially the air pollution.

The PM$_{2.5}$ concentration were negatively correlated with wind speed, with the correlation coefficient of -0.74, showing that high wind speed could decrease pollution levels. The correlation coefficient between PM$_{2.5}$ and PWV is small, correlating to the small moisture content in Beijing in winter, which contributes a little to the formation of haze pollution.

In conclusion, as a powerful tool to simulate all of the atmospheric parameters, WRF and WRF-Chem provide a selective choice for scholars to do researches about the air pollution and put forward to suggestions for the government.

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