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A budget analysis of the formation of haze in Beijing

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HIGHLIGHTS

- A haze episode with a very strong variability in Beijing was analyzed.
- WRF-Chem and a box model are used for the budget analysis of haze formation.
- Under calm winds, a heavy haze can be formed in one (1) day.
- The wind speed to balance emission-clean processes was calculated.

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ABSTRACT

During recent winters, hazes often occurred in Beijing, causing major environmental problems. To understand the causes of this "Beijing Haze", a haze episode (from Oct. 21 to Oct. 31, 2013) in Beijing was analyzed. During the episode, the daily mean concentration of fine particulate matter ($PM_{2.5}$) reached a peak value of 270 μg/m^3 on Oct. 28, 2013, and rapidly decreased to 50 μg/m^3 the next day (Oct. 29, 2013). This strong variability provided a good opportunity to study the causes of a "Beijing Haze". Two numerical models were applied for this study. The first model is a chemical/dynamical regional model (WRF-Chem). This model is mainly used to study the effects that weather conditions have on $PM_{2.5}$ concentrations in the Beijing region. The results show that the presence of high air pressure in northwest Beijing (NW-High) generally produced strong northwest winds with clean upwind air. As a result, the NW-High played an important role in cleaning Beijing's PM. However, the NW-High's cleaning effect did not occur in every situation. When there was low air pressure in southeast Beijing (SE-Low) accompanied by an NW-High, an air convergent zone appeared in Beijing. The pollutants became sandwiched, producing high $PM_{2.5}$ concentrations in the Beijing region. The second model used in this study is a box model, which is applied to estimate some crucial parameters associated with the budget of $PM_{2.5}$ in the Beijing region. Under calm winds, the calculations show that continuous local emissions rapidly accumulate pollutants. The $PM_{2.5}$ concentrations reached 150 μg/m^3 and 250 μg/m^3 within one (1) day and two (2) days, respectively. Without horizontal dilution, this estimate can be considered as an upper time limit (the fastest time) for the occurrences of haze events in the Beijing region. The wind speed (WS_b) is calculated for the balance between the continuous emissions and atmospheric clean processes. The results show that the WS_b is strongly dependent on the planetary boundary layer (PBL) height and the wind direction. Under SE-Low weather conditions, the WS_b is 2 m/s with a higher PBL height (700 m). However, under lower PBL heights, the WS_b rapidly increases, reaching 4.5 m/s and 7.0 m/s with PBL heights of 300 m and 200 m, respectively. In contrast, under NW-High weather conditions, the WS_b reduces to 2.5 m/s and 4.0 m/s. These results suggest that when the prevailing wind in Beijing is a northwest wind (with wind speeds of >4 m/s), particulate matter (PM) begins to decrease.

1. Introduction

Beijing, the capital of China, is a mega city with a population of more than 20 million. In recent years, the city has experienced

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rapid economical development and growth. For example, in 2011, the number of automobiles was 5 million, and by 2016, this number is expected to be 6 million. In 2013, the increase of gross domestic product (GDP) was 7.7%. One negative byproduct of this rapid economical development, especially in the past two decades, is that Beijing has been forced to endure heavy air pollution, with particulate matter (PM) being one of its top pollutants (Chan and Yao, 2008). The high concentration of PM causes a wide range of environmental consequences. According to a study by Tie et al. (2009), exposure to extremely high particle concentrations leads to a great increase of lung cancer cases. High PM concentrations also significantly reduce the range of visibility (Deng et al., 2008; Cao et al., 2012) and enhance atmospheric acidity (Cao et al., 2013) in China's large cities. However, high PM concentrations also have a bright side – they reduce the photochemical production of ozone, which is another harmful pollutant affecting human health (Tie et al., 2005; Bian et al., 2007; Tie and Cao, 2009; Tie et al., 2013).

In the last decade, extensive efforts have been made to characterize the sources, properties, and processes of PM in Beijing. Recent studies indicate that a large mass fraction of ambient PM in Beijing is fine particles, of which carbonaceous particles, sulfate, nitrate, and ammonium are major components (Guinot et al., 2007; He et al., 2001; Yang et al., 2011). The different sources that contributed to Beijing's PM concentrations have also been studied (Zhang et al., 2013). Despite progress made by previous studies, there are still some important questions to be answered and addressed. In recent years, high concentrations of particle concentrations are occurring frequently in Beijing and its surrounding regions (Zhang et al., 2006, 2009), and a very large variability of PM concentrations is often characterized (He et al., 2014). It is interesting to note that PM concentrations increase exponentially in the span of a few days, with non-linear growth. According to a study by Quan et al. (2013), this rapid increase in PM concentrations might involve an interaction between particles and the planetary boundary layer (PBL); however, more studies are still needed in this area.

In order to analyze the causes and variability of PM in Beijing, a high aerosol pollution episode, characterized by a large variability of PM concentration is studied. The episode occurred between Oct. 21 and Oct. 31, 2013. During the episode, the daily mean concentration of $PM_{2.5}$ reached a peak value of 250 $\mu g/m^3$ on Oct. 28, 2013, and rapidly decreased to 50 $\mu g/m^3$ the next day (Oct. 29, 2013). This strong variability provided a good opportunity to study the causes of a "Beijing Haze". Two numerical models are applied in this study. The first model is a chemical/dynamical regional model (WRF-Chem). The WRF-Chem model is a state of the art regional dynamical/chemical/aerosol model. This model is mainly applied to study the effects of weather conditions on the regional transport and distribution of PM. The second model is a box model, and this model is mainly used for the budget analysis of the mass of PM in Beijing, such as quantifying the effect of surface emission accumulation on the growth of PM and the advection of PM with different meteorological parameters (wind direction, wind speed, and the PBL height) in the Beijing region.

2. Methods

Numerical models are extensively used in this study. The first model is a state of the art regional dynamical/chemical/particle model (WRF-Chem), and the second model is a box model. Detailed descriptions of the models are as follows:

2.1. WRF-Chem model

The main objectives of this study are to apply a regional chemical/dynamical model, to analyze measurements, to evaluate the model by comparing the model result to the measured data, and to study $PM_{2.5}$ variability in the Beijing region. The model used in this study is a regional chemical/transport model (Weather Research and Forecasting Chemical model – WRF-Chem). There are two major parts of the model, namely, a dynamical model (WRF) and a chemical model (Chem). The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the National Oceanic and Atmospheric Administration, the Air Force Weather Agency (AFWA), the Naval Research Laboratory, Oklahoma University, and the Federal Aviation Administration (FAA). The WRF model is a fully compressible and non-hydrostatic Euler model. Thirty-five vertical levels are used in a stretched vertical grid with spacing ranging from 50 m near the surface, to 500 m at 2.5 km and 1 km above 14 km. The model employs the Lin microphysics scheme (Lin et al., 1983), the Yonsei University (YSU) PBL scheme (Noh et al., 2001), the Noah land-surface model (Chen and Dudhia, 2001), the long-wave radiation parameterization (Mlawer et al., 1997), and the shortwave radiation parameterization (Dudhia, 1989). Detailed information regarding the parameters used in the WRF model, such as the PBL scheme, the land surface scheme, the microphysics scheme, and the cumulus cloud scheme can be found at the WRF website (http://www.wrf-model.org/wrfadmin/docs/arw_v2.pdf), and the WRF model is documented by Skamarock et al. (2008).

In addition to dynamical calculations, a chemical model is "online" coupled with the WRF model (WRF-Chem). Grell et al. (2005) provides more details about the WRF-Chem. The version of the model used in the present study (Tie et al., 2007) includes an online calculation of dynamical inputs (winds, temperature, boundary layer, clouds, etc.); transport (advection, convection, and diffusion); dry deposition (Wesely, 1989); gas phase chemistry, radiation, and photolysis rates (Madronich and Flocke, 1999; Tie et al., 2003), and surface emissions (including an online calculation of biogenic emissions). The chemical mechanism used is the RADM2 (Regional Acid Deposition Model, version 2) gas-phase chemical mechanism (Chang et al., 1989), which includes 158 reactions among 36 species. The aerosol modules used in the study are described as the aerosol module developed by EPA CMAQ (version 4.6) (Binkowski and Roselle, 2003). The inorganic aerosols are predicted in the WRF-Chem model using ISORROPIA (version 1.7) (http://nenes.eas.gatech.edu/ISORROPIA/), which calculates the composition and phase state of an ammonium–sulfate–nitrate–chloride–sodium–calcium–potassium–magnesium–water inorganic aerosol in thermodynamic equilibrium with gas phase precursors. The secondary organic aerosol (SOA) formation is simulated using a non-traditional SOA model including the volatility basis-set modeling method in which primary organic components are assumed to be semi-volatile and photo-chemically reactive and are distributed in logarithmically-spaced volatility bins as previously described (Li et al., 2011).

In this study, the domain of the numerical simulation is 1000 × 1000 km in a horizontal region that is centered in Beijing City with a resolution of 10 km. The chemical lateral boundary conditions are constrained from the result of a global chemical transport model (MOZART–Model for OZone and Related chemical Tracers), with the aerosol formation modules (Tie et al., 2001; Tie et al., 2005; Emmons et al., 2010). The model ran from Oct. 16 to Oct. 31, 2013, and only the results from the last 10 days (from Oct. 21 to Oct. 31) were used (the results from the first five (5) days are considered as spin up of the model calculations). The hourly