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# A modeling study of severe winter haze events in Beijing and its neighboring regions

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ABSTRACT

A Regional Air Quality Model System (RAQMS) with a series of ground observations and satellite retrievals was utilized to investigate haze events in January 2013, in which the observed maximum daily mean surface $PM_{2.5}$ concentrations in Beijing exceeded 400 μg $m^{-3}$. The model predicted a monthly mean $PM_{2.5}$ concentration of 200–300 μg $m^{-3}$ over southern Beijing, Tianjin, and the southern Hebei province, with most aerosols restricted within 500 m above ground. Meteorology played an important role in haze formation. Aerosols were transported into Beijing and Tianjin from the south to the north at altitudes below 1.5 km during haze episodes. Sensitivity simulations revealed that nearly 44% of surface $PM_{2.5}$ in Beijing was contributed by local emissions with the remaining 56% coming from surrounding sources in terms of monthly mean and the outside contribution increased to 62% during episode 2, suggesting the important influence of regional trans-boundary transport on Beijing haze pollution.



## 1. Introduction

Recently, more and more attention has been paid to $PM_{2.5}$ (particulate matters with aerodynamic diameters ≤2.5 μm) in China because of their significant adverse impact on air quality and human health. Aerosols can also influence radiation transfer and climate system through scattering/absorbing solar radiation or modifying cloud microphysical property by acting as cloud condensation nuclei (Forster et al., 2007). Megacities in China have been suffering from air pollution in recent years (Chan and Yao, 2008; Tie and Cao, 2009; Zhang et al., 2012a) as a result of the continuous growth in economics and urbanization. Fine particles originated from direct release of anthropogenic emissions or chemical formation of a series of gas precursors (such as sulfur dioxide, nitrogen oxides, etc.) are major pollutants during haze pollution episode (Zhao et al., 2009; Zhang et al., 2013) and exert stronger impacts on human health, air quality, and radiation transfer due to their longer lifetime in the atmosphere, more effective attenuation of solar radiation, and easy penetration into human respiration system. Haze events in China often occurred in winter due to increasing energy consumption for heating and atmospheric stability. Haze pollution is characterized by very high $PM_{2.5}$ concentration, low visibility, as well as the increasing fraction of toxic pollutants (Zhuang et al., 2014). Beijing, as the capital of China and one of the megacities with population more than 20 million, has been experiencing haze problem for many years which is attributed to the combined influences from local emission, regional transport, complex topography, as well as typical meteorology (Li et al., 2011a; Liu et al., 2013; Zhang, et al., 2012b). In China, haze day is defined as the air turbid phenomenon with visibility less than 10 km caused by dry and invisible airborne fine particles according to the criteria prescribed by the China Meteorological Administration. Several severe haze events appeared continuously in the north China plain (NCP) including Beijing, Tianjin and Hebei Province during January 2013, in which the frequency of haze day during a month was maximum in the past decades. Haze pollutions in January 2013 have been studied focusing on evolution process and chemical composition based on in-situ observations (Wang et al., 2014a; Sun et al., 2014; Yang et al., 2015), as well as source contribution and control policy implication by model simulations (Wang et al., 2014b). However, the sources and formation of haze remain unclear and require further investigation.

In this study, a Regional Air Quality Model System (RAQMS) was adopted to investigate haze events in January 2013. Pollutant concentration, surface visibility, aerosol optical depth, and vertical profile of aerosol extinction coefficient were numerically investigated with ground measurements and satellite retrievals. The regional transport features and the relative contributions of local and regional emissions to $PM_{2.5}$ level in specific regions were also explored. This study would be valuable in further understanding the mechanisms and sources of haze pollution in Beijing and the NCP region.

## 2. Methodology

### 2.1. Model description

RAQMS is a three-dimensional Eulerian model constructed on a spherical and terrain-following coordinate system. It includes a series

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of key processes of atmospheric pollutants such as emission, advection, diffusion, multiphase chemistry, dry deposition, in-cloud mixing, and below-cloud scavenge. The advection process was calculated using the algorithm of Walcek and Aleksic (1998). The vertical eddy diffusivity was parameterized by the approach proposed by Byun and Dennis (1995). The dry deposition process of gases was parameterized following Walmsley and Wesely (1996), while that of aerosols was calculated as inverse of total resistances plus the gravitational settling term (Han et al., 2004). The SAPRC99 (Statewide Air Pollution Research Center) mechanism proposed by Cater (2000) was applied for gas-phase chemistry. The ISORROPIA II model (Fountoukis and Nenes, 2007) was incorporated into RAQMS to account for thermodynamic equilibrium processes. The formation of secondary organic aerosols from anthropogenic and biogenic VOC precursors was calculated based on a bulk yield scheme (Lack et al., 2004). Heterogeneous reactions between dust aerosol and gases were considered by Li and Han (2010). The subgrid cloud mixing, scavenging and aqueous chemistry were treated with modules similar to that in Chang et al. (1987). Inorganic and carbonaceous aerosols were assumed to fit log-normal distribution and settle in fine mode. Soil dust was divided into 10 size bins of 0.43–42 μm. RAQMS has ever been applied to study a series of environmental issues regarding tropospheric ozone, acid deposition, dust storm and anthropogenic aerosols over East Asia (Han et al., 2004, 2008a; Han, 2007; Li et al., 2011b). It also participated in the Model InterComparison Study for Asia phase II (MICS-Aisa II) project (Han et al., 2008b).

The $\kappa$ (kappa) parameterization was developed in recent years (Petters and Kreidenweis, 2007) and was incorporated in RAQMS to account for aerosol hygroscopic growth:

$$g(RH) = \left(1 + \kappa \times \frac{RH}{1-RH}\right)^{\frac{1}{3}} \quad (1)$$

where $g(RH)$ denotes the aerosol diameter hygroscopic growth factor and $RH$ is the fractional relative humidity. The hygroscopicity parameter $\kappa$ for inorganic components (sulfate, nitrate, and ammonium), black carbon, primary organic carbon, secondary organic carbon, and dust was set to 0.65, 0, 0.001, 0.1 and 0.01, respectively (Riemer et al., 2010). Aerosol optical properties such as extinction coefficient were calculated by a Mie-theory based parameterization (Ghan and Zaveri, 2007). The advantage of this parameterization is that aerosol optical properties were precalculated and then fitted by Chebyshev polynomials to create a table of polynomial coefficients. By using this table, the calculation of aerosol optical properties became much faster than the traditional Mie code.

Surface visibility was calculated in the model by using Koschmieder's formula (Nebuloni, 2005):

$$\mathrm{VIS} = \frac{3.91}{b_{\mathrm{ext}}} \quad (2)$$

where $b_{\mathrm{ext}}$ is the aerosol extinction coefficient ($\mathrm{km}^{-1}$) at 550 nm.

In this work, RAQMS was configured with a horizontal resolution of 0.5° × 0.5° throughout the domain from 75°E to 145°E and from 20°N to 50°N, and the Beijing–Tianjin–Hebei region (112°E to 120°E, 35°N to 43°N) was the focus of this study (Fig. 1). Twelve vertical layers stretched unequally from ground to about 10 km, with the lowest layer being 50 m. Simulation was conducted from 27 December 2012 to the end of January 2013 with the first 5 days as model spin-up.

Monthly varied anthropogenic emission inventories of CO (carbon monoxide), $NO_x$ (nitrogen oxides), $SO_2$ (sulfur dioxide), BC (black carbon), POC (primary organic carbon), and NMVOCs (non-methane volatile organic compounds) were obtained and used in this study. Emission inventory from MEIC (Multi-resolution Emission Inventory for China) model developed by Tsinghua university (http://meicmodel.org) was applied for China, whereas INTEX-B (Intercontinental Chemical Transport Experiment-Phase B) emission inventory (Zhang et al., 2009) was used for the rest of the domain (such as Japan, the Korean peninsula, southeast Asia, etc.). The MEIC and INTEX-B inventories were based on the year 2010 and 2006, respectively. Monthly mean biomass burning emissions were derived from the Global Fire Emission Database version 3.1 (Van der Werf et al., 2010). Monthly biogenic emissions of isoprene and monoterpene were derived from Global Emissions Inventory Activity (GEIA, www.geiacenter.org/). The above emission inventories have the same grid resolution as that in RAQMS. Boundary conditions of gas and aerosol components were provided by global model results of MOZART (Model for OZone And Related chemical Tracers, http://www.acd.ucar.edu/wrf-chem/mozart.shtml).

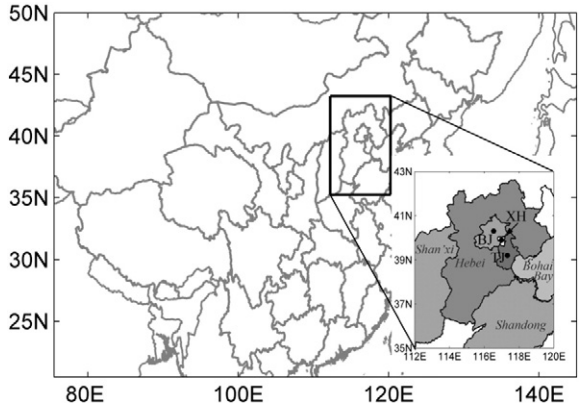


**Fig. 1.** Simulation domain (75°E to 145°E, 20°N to 50°N) and site locations (BJ: Beijing; XH: Xianghe; TJ: Tianjin). The small domain inside indicates the focusing Beijing–Tianjin–Hebei region (112°E to 120°E, 35°N to 43°N).

The Weather Research and Forecasting model (WRF, version 3.5.1) was applied to provide meteorological fields to drive RAQMS. WRF was described in detail in Skamarock et al. (2008). The WRF model was configured with 36 km resolution. 1° × 1° NCEP (National Centers for Environmental Prediction) reanalysis data with temporal resolution of 6-hour was used to provide initial and boundary conditions.

### 2.2. Observation data

Surface observations of meteorological variables including wind speed at 10 m (WS10) and air temperature at 2 m (T2) at 00:00, 06:00, 12:00, and 18:00 (UTC), as well as daily mean observation of relative humidity at 2 m (RH2) (due to the lack of 6 hourly data) and horizontal visibility (VIS) in Beijing and Tianjin were obtained from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn) and used for model evaluation.

Daily mean concentrations of $SO_2$, $NO_2$ (nitrogen dioxide), and $PM_{10}$ (particulate matters with aerodynamic diameters ≤10 μm) in Beijing and Tianjin were from the surface observation of China National Environmental Monitoring Center. The daily data was averaged from 12:00 the prior day to 12:00 this day (local standard time). Daily mean $PM_{2.5}$ concentration in Beijing during January 2013 was derived from the Air Quality Index (AQI) data collected from the Beijing Municipal Environmental Protection Bureau (http://www.bjepb.gov.cn). When $PM_{2.5}$ is the primary pollutant, the AQI data can be converted to $PM_{2.5}$ concentration according to the Technical Regulation on Ambient Air Quality Index of China as the following:

$$C = \frac{C_i - C_j}{I_i - I_j} \times (I - I_j) + C_j \quad (3)$$

where $I$ is the reported AQI and $C$ is the daily mean concentration of primary pollutant ($SO_2$, $NO_2$, Ozone, $PM_{10}$, or $PM_{2.5}$). The $I_i$ and $I_j$ represent AQI grading limits greater and smaller than $I$; $C_i$ and $C_j$ denote the pollutant concentrations corresponding to $I_i$ and $I_j$, respectively. There are seven AQI grades (50, 100, 150, 200, 300, 400, and 500) and the corresponding