Atmospheric Environment 159 (2017) 147–161

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

The contribution of residential coal combustion to $PM_{2.5}$ pollution over China's Beijing-Tianjin-Hebei region in winter

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HIGHLIGHTS

- WRF-CMAQ model simulates December haze over the Beijing-Tianjin-Hebei region.
- Contribution of residential coal combustion to $PM_{2.5}$ pollution is quantified using Brute Force approach.
- Langfang was the city most affected by residential coal combustion in the Beijing-Tianjin-Hebei region.
- Decrease of household coal consumption could help inhibit the growth of $PM_{2.5}$ in the night of haze episodes.

ARTICLE INFO

Article history:
Received 15 December 2016
Received in revised form
29 March 2017
Accepted 30 March 2017
Available online 1 April 2017

Keywords:
Beijing-Tianjin-Hebei region
$PM_{2.5}$
Residential coal combustion
Urban air pollution
WRF-CMAQ
Air quality modeling

ABSTRACT

The Beijing-Tianjin-Hebei (BTH) region experiences severe haze episodes throughout the year, and especially during the winter heating season. Residential combustion of coal has increasing been cited as a possible source for the $PM_{2.5}$ pollution that causes the haze episodes. To investigate these claims, a WRF-CMAQ system is used to reproduce the regional haze episodes observed during December 2015. The contribution of residential coal combustion to $PM_{2.5}$ concentrations in the BTH region is quantified using the Brute Force approach. Across the region, residential coal combustion contributed 46% of the monthly averaged $PM_{2.5}$ concentration (3% each from Beijing and Tianjin and 40% from Hebei Province). During the haze episodes, the contribution varied between 30 and 57%. At the city scale, the contribution ranged from 22 to 58% averaged across the month and 15–65% during the haze episodes. Langfang was the city that was the most affected by residential coal combustion in the BTH region. The large contribution to air pollution in Tianjin and Beijing from households in Hebei Province suggests that regional control measures are required.

1. Introduction

The Beijing-Tianjin-Hebei (BTH) region is one of the largest and most dynamic economic zones in northern China. It extends south to north across the North China Plain and the Inner Mongolian Plateau, includes two megacities—Beijing and Tianjin—and 11 prefecture-level cities in the Hebei Province. Rapid economic expansion and urbanization has caused this region to suffer extremely frequent and severe haze events, especially in winter when coal is burned for heating. Seven of the cities in the BTH region were among China's ten most polluted in 2015, eight were included in 2014 (MEP, 2015, 2016). On nearly half (48%) of the days in 2015, the ambient $PM_{2.5}$ (pollutant particles with an aerodynamic diameter ≤ 2.5 μm) concentration in BTH exceeded the class II daily average limit (75 μg/m^3) according to the National Ambient Air Quality Standard (NAAQS) and the peak hourly concentration even surpassed 900 μg/m^3 in the December (CNEMC, 2015). Around the same time, Beijing issued the first red alert for air pollution in its history.

A series of recent publications have identified the major sources of ambient air pollution in China (Huang et al., 2015; Li et al., 2016c; Miao et al., 2015; Wang et al., 2015a; Zíková et al., 2016). In particular, Liu et al. (2016) found pollutant emissions from residential households contributed significantly, while this pollutant source has been relatively neglected. Although its use satisfies

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http://dx.doi.org/10.1016/j.atmosenv.2017.03.054
1352-2310/

residential energy needs, air pollution from household use of unprocessed coal, the largest source of household energy, deserves more attention (Chen et al., 2015; Li et al., 2016b). According to surveys carried out by the Beijing city (CAEPI, 2016) and Zhi et al. (2015), the use of residential coal had a high coverage (>80% in rural Beijing, 97% in rural Baoding). However, the consumption was significantly underestimated in the China Energy Statistical Yearbook (Zhi et al., 2015). One issue with residential coal combustion is that the process of burning it lacks the $PM_{2.5}$ control measures used on larger industrial burners. This means that $PM_{2.5}$ emission rates per gram of coal can be 100 times larger than those of coal-fired power plants (Li et al., 2016a; Zhang et al., 2008). When assessed together, the aggregate emissions from so many small sources produce much higher emissions than those from other sectors (Wang et al., 2014b). In addition, because the pollution from residential coal use is emitted closer to where people live, it has a greater impact on urban air quality and human health.

Significant effort and a number of control measures have focused on curbing emissions from the power, transport and industry sectors (Sheehan et al., 2014). Focusing on improving air quality, China's National Development and Reform Commission (NDRC) recently issued a planning document that targets limiting $PM_{2.5}$ annual mean concentrations to 73 μg/m^3 in 2017, and 64 μg/m^3 in 2020. In addition to tackling emissions from the sectors mentioned above, controlling emissions from residential coal combustion could be an effective approach to achieve the NDRC's goal. To investigate the impact of emissions from residential coal use in winter, we use air quality and weather models with the Brute Force method to quantify $PM_{2.5}$ emissions over the BTH region. Contribution analyses are then carried out at both regional and city scale and three scenarios are employed to study the effects of different emission-reduction plans.

2. Model description and verification

2.1. Meteorological model and chemical-transport model

The Models-3 Community Multiscale Air Quality model (CMAQ) employed in this study is a three-dimensional Eulerian air quality model released by U.S. Environmental Protection Agency in 1998. Unlike the two previous generations of air quality models which could only simulate simple physical progresses or handle one specified air pollution issue, CMAQ is based on the "one atmosphere" perspective. This means that it can operate at multiple scales, can reproduce nearly all of the physical and chemical processes that affect transport, transformation and deposition of pollutants, and can deal with multiple air pollutants and their interactions, simultaneously (Binkowski and Roselle, 2003; Byun and Schere, 2006; Wang et al., 2013; Xue et al., 2013).

The Weather Research and Forecasting (WRF) model (Michalakes et al., 1998; Wang and Ma, 2011) is a fully compressible and non-hydrostatic (with a hydrostatic option) mesoscale weather prediction model developed after the Fifth-generation NCAR/Penn State Mesoscale model (MM5). It uses an Arakawa C-grid in the horizontal direction and a terrain-following hydrostatic pressure coordinate in the vertical direction. A time-split, high-order Runge-Kutta method is used to integrate the conservative formulation. According to the dynamical cores, WRF can be divided into the Advanced Research WRF (ARW) and the Non-hydrostatic Mesoscale Model (NMM). The WRF-CMAQ/MM5-CMAQ modeling system provides a powerful tool for scientifically analyzing the impact of policy regulations. The model has been applied to analyze policy changes brought in at the time of the 2008 Beijing Olympics (Streets et al., 2007) and to study the impact of highly polluting processes during January 2013 when haze levels in northern China were the highest they've been in recent decades (Cheng et al., 2015).

In this study, two nested domains were simulated. A coarse-grid domain with a grid resolution of 36 km × 36 km was employed to cover the whole East Asia region. At a more local level, a fine-grid domain with a grid resolution of 12 km × 12 km was used, which covered most parts of northeastern China, including the BTH region and some surrounding provinces. The coarse-grid simulations were used to provide boundary conditions for the fine-grid simulations. All of the following analyses are based on the results from the fine-grid simulations.

The first-guess fields used to initialize the WRF model were obtained from the NCEP FNL Operational Global Analysis datasets (horizontal resolution 1° × 1°, 6-h interval) and the ERA-Interim global atmospheric reanalysis datasets (horizontal resolution 0.75° × 0.75°, 6-h interval). These were coupled with different boundary-layer options using the Yonsei University (YSU) scheme (Hong et al., 2006) and the ACM2 (Pleim) PBL (ARW) scheme (Pleim, 2007) in different configuration scenarios. The Kain-Fritsch (new Eta) scheme (Kain and Fritsch, 1993) was used for cumulus parameterization. The Rapid Radiative Transfer Model (RRTM) (Mlawer et al., 1997) and Dudhia scheme (Dudhia, 1993) were chosen as the longwave and shortwave schemes, respectively. A number of other physical options were used in the various scenarios, including the WRF Single Moment (WSM) 3-class simple ice scheme (Hong et al., 2004), the revised MM5 Monin-Obukhov (Janjic) scheme (Jiménez et al., 2012) and the Unified Noah land-surface model (Tewari et al., 2004). The outputs of the WRF model were post-processed with the Meteorology Chemistry Interface Processor (MCIP) to provide valid meteorological fields to be used with CMAQ.

In the CMAQ simulations, the default profile was used to provide the boundary conditions for simulations with the coarse grid. The concentration fields from the coarse grid were then used to provide the time-varying boundary conditions for the fine-grid-resolution grids to minimize the influence of the boundary conditions. A spin-up period of 10 days (November 21–30, 2015) was used to decrease the impact of the initial conditions. The vertical grid structure was divided into 20 layers ranging from the surface to the model top (50 hectopascals). The corresponding sigma levels were 1.0000, 0.9975, 0.9950, 0.9900, 0.9800, 0.9700, 0.9600, 0.9400, 0.9200, 0.9000, 0.8750, 0.8500, 0.8200, 0.7550, 0.6850, 0.5800, 0.5100, 0.4400, 0.3200, 0.2000 and 0.0000. Regarding chemical mechanisms, the Statewide Air Pollution Research Center, Version 1999 (SAPRC-99) (Carter, 2000) has been shown to perform well over northern China during haze episodes and was chosen as the gas-phase chemical mechanism (Wang et al., 2016b). The fifth-generation modal CMAQ aerosol model with a sea salt extension (Binkowski and Shankar, 1995) was chosen as the aerosol module. Dust emissions were not considered in this work.

2.2. Emission inventory

The emission inventory is an important factor for achieving reasonable simulation results. In this work, the Multi-resolution Emission Inventory for China (MEICv2012, http://www.meicmodel.org) and the Regional Emission Inventory in Asia (REASv2.1, http://www.nies.go.jp/REAS/) were used as the domestic and international emission inventories, respectively. The proportion of emissions in the residential sectors was taken from a recent residential sector emission inventory (Cheng et al., 2017) which was updated to include the latest survey results.

Fig. 1 shows a comparison of the updated (2013), MEIC2012, and coal-only residential sector emission inventories. Marked changes occurred between 2012 and 2013. Over the BTH region the