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Assessment of winter air pollution episodes using long-range transport modeling in Hangzhou, China, during World Internet Conference, 2015☆

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A winter air pollution episode was observed in Hangzhou, South China, during the Second World Internet Conference, 2015. To study the pollution characteristics and underlying causes, the Weather Research and Forecasting with Chemistry model was used to simulate the spatial and temporal evolution of the pollution episode from December 8 to 19, 2015. In addition to scenario simulations, analysis of the atmospheric trajectory and synoptic weather conditions were also performed. The results demonstrated that control measures implemented during the week preceding the conference reduced the fine particulate matter ($PM_{2.5}$) pollution level to some extent, with a decline in the total $PM_{2.5}$ concentration in Hangzhou of 15% (7%–25% daily). Pollutant long-range transport, which occurred due to a southward intrusion of strong cold air driven by the Siberia High, led to severe pollution in Hangzhou on December 15, 2015, accounting for 85% of the $PM_{2.5}$ concentration. This study provides new insights into the challenge of winter pollution prevention in Hangzhou. For adequate pollution prevention, more regional collaborations should be fostered when creating policies for northern China.

1. Introduction

Air pollution has recently become a widespread concern in China because of its numerous consequences such as poor visibility (Wu et al., 2012) and regional climate variations (Pipal and Gursumeeran Satsangi, 2015). Air pollution episodes are usually characterized by abnormally high concentrations of air pollutants during prolonged periods. Recent evidence showed that air pollution episodes shorten the lifespan of citizens and contribute to serious illnesses including cardiovascular diseases, respiratory issues, and cancer (Brook et al., 2010; Dunea et al., 2016; Peplow, 2014). In certain regions, particularly in economically developed areas such as the Beijing-Tianjin-Hebei (BTH), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD), air pollution is even worse (van Donkelaar et al., 2010; Zhang and Cao, 2015). Evidence suggests that fine particulate matter (airborne particles with an aerodynamic diameter of less than 2.5 μm [$PM_{2.5}$]) is an important contributor to air pollution, especially in winter (Cheng et al., 2013; Zhou et al., 2014). The sources of $PM_{2.5}$ include the directly emitted aerosols (primary $PM_{2.5}$) and the secondary aerosols (secondary $PM_{2.5}$) from gaseous precursors such as SO_2, NO_x, and volatile organic compounds (VOCs) through chemical reactions (Huang et al., 2014). In addition to major emission sources, winter pollution levels are also closely related to specific weather conditions such as atmospheric stability (Gao et al., 2015; Yang et al., 2015), long-range and regional transport of clean and polluted air masses (Fu et al., 2016; Zheng et al., 2015).

To reduce potential urban air pollution, short-term emission control measures are usually implemented during major events in China, such as the 2008 Beijing Olympics (Schleicher et al., 2012; Wang et al., 2010), the 2010 Guangzhou Asian Games (Liu et al.,

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2013), the 2010 Shanghai World Expo (Lin et al., 2013), the 2014 Nanjing Youth Olympics (Zhao et al., 2017), and the 2015 Beijing Parade Blue (Xu et al., 2017). Both the emission abatement efforts and meteorological conditions were confirmed to vary across different regions. The common successful control measures are regional cooperation and joint control of coal burning, industrial production, and traffic volume (Feng and Liao, 2016). However, all these events are held in warmer months, and the feasibility of real short-term control measures during winter has not been sufficiently investigated in China, especially under extreme meteorological conditions, which may bring long-range transport of pollutants.

In the recent years, air quality modeling has been widely utilized to investigate the underlying mechanisms of accumulation and propagation of pollutants (Bei et al., 2016; Gupta and Mohan, 2013; Zhang et al., 2012a, 2012b). Compared with expensive and spatially limited measurement systems, modeling systems can be easily used for extensive simulations of hypothetical emission scenarios for pollution prevention studies. One type of regional online coupled meteorology and chemistry model, the Weather Research and Forecasting with Chemistry (WRF-Chem) model (Grell et al., 2005), has been proven to be reliable and can be applied to provide an operational forecast of particulate pollution throughout China (Zhou et al., 2017). This model properly considers the interactions among atmospheric physics, dynamics, and composition. Baklanov et al. (2014) and Kukkonen et al. (2012) have reviewed in depth its advantages.

In this study, long-range transport modeling based on a WRF-Chem model is used to elucidate the characteristics of a particular winter pollution episode observed during the Second World Internet Conference, 2015. The effectiveness of short-term emission control measures in winter has been investigated, and the underlying causes for the particular pollution episode have been discussed. The manuscript is organized as follows. Section 1 has already presented the key aspects related to the importance of the study. Section 2 describes the modeling system and simulation methods. Section 3 presents an evaluation of model performance and modeling outcomes from meteorological and chemical perspectives. Major findings and policy implications are discussed in Section 4 and the study findings are summarized in Section 5.

2. Material and methods

2.1. Modeling system

A meteorological and chemistry modeling system is a group of models used to make gridded predictions of hourly ambient pollutant concentrations. The WRF-Chem model enables simulations of two-way interactions between physical and chemical processes. It includes predictive equations for emissions, turbulent mixing, transport, and transformation, and the fate of trace gases as well as aerosols (Grell et al., 2005). In this model, aerosols are predicted by simultaneously simulating physical processes, such as nucleation, coagulation, condensation, deposition, and cloud interaction, and chemical processes, such as aqueous- or gaseous-phase reactions. In this study, major parameterization schemes were selected by considering both numerical accuracy and efficiency based on our high-performance computer clusters (2688-CPU core IBM clusters, 5376 GB RAM), and summarized in Table S1 of the supplementary material. Double-nested simulations were conducted with smoothing and feedback from the inner to outer domain. The outer domain covered eastern China with 112 (W−E) × 121 (S−N) grids at a horizontal resolution of 30 km, and the inner domain focused on the YRD regions with 110 (W−E) × 125 (S−N) grids at a horizontal resolution of 6 km, as shown in Fig. 1a. Thirty-one nonlinear vertical layers were applied with finer vertical resolutions near the surface and top layer of 100 hPa. All these layers were georeferenced in a Lambert projection and the associated coordinate system.

The digital terrain model (DTM) and land-use data were obtained from the US Geological Survey database (Brown et al., 1993). The meteorological boundary and initial conditions were obtained from the National Centers for Environmental Prediction (NCEP) global objective final analysis (FNL) data (http://rda.ucar.edu/datasets/ds083.2/). Grid nudging was applied every 6 h. The chemical boundary and initial conditions were interpolated from the simulation results of the global Model for Ozone and Related Chemical Tracers version 4, MOZART4 (Emmons et al., 2010). Spin-up was performed for 7 days and used for simulations for minimizing the influence of meteorological and initial chemical conditions. The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler et al., 2016) was applied for calculations of atmospheric backward trajectory for 100 m (above ground level) in Hangzhou, by using a meteorological data set from the NCEP Global Data Assimilation System (GDAS, 0.5-degree resolution). Multiple trajectories were grouped into atmospheric transport corridors by using a clustering technique (Stein et al., 2015).

Anthropogenic emissions, such as primary SO_2, NO_x, CO, NH_3, $PM_{2.5}$, and VOCs, were derived from the Multi-resolution Emission Inventory for China (0.25- × 0.25-degree resolution, http://www.meicmodel.org). These sector-based emissions data, including contributions from power plants, industry, residences, transportation, and agriculture, were formatted into gridded hourly emissions by using the temporal profiles (Wang et al., 2011). Of particular concern was the desert land-cover (Chen et al., 2003) and strong anthropogenic emissions in northern China (Fig. S1), associated with a high population density (Fig. 1a), as reported by Xu et al. (2015). Gaseous natural emissions (biogenic emissions) were projected using the Model of Emission of Gases and Aerosols from Nature (Guenther et al., 2006). Natural particulate emissions (mainly windblown dust and sea salt) were calculated using an online method based on surface features and meteorological fields (Baklanov et al., 2014). Other uncritical emissions (e.g., lightning, aviation, and sailing ships) were not considered in the present study.

2.2. Emission reductions achieved by control measures

The Second World Internet Conference was held in Wuzhen, a town near Hangzhou, South China from December 16 to 18, 2015. To reduce potential air pollution in this region, a series of short-term emission control measures were applied during the week preceding the conference, from December 8 to 19, 2015. According to the official documents, the mitigation areas were divided into two circles, the core and active areas (Fig. 1b), including 1067 and 1308 major regulatory enterprises, respectively. The control measures focused on reducing pollutant emissions from power plants, industry, and transportation. Table 1 summarizes the details and magnitude of the mitigation plan regarding the control measures. During the campaign period, the control measures reduced SO_2, NO_x, $PM_{2.5}$, and VOC emissions by 1,437, 1,505, 891, and 2982 tons in the core area, respectively, and by 990, 1,252, 1,197, and 1663 tons in the active area, respectively. The corresponding total emission reduction rates of SO_2, NO_x, $PM_{2.5}$, and VOCs were estimated to be 43%, 43%, 55%, and 47%, respectively.

2.3. Model evaluation protocols

To enhance the credibility of the model result's interpretation, the model's performance was first evaluated based on observed