Potential Air Quality Improvements from Ultralow Emissions at Coal-fired Power Plants in China

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ABSTRACT

To assess the effectiveness of nationwide ultralow emission policies for coal-fired power plants on air quality in China, we simulated several criteria pollutants concentrations using the Weather Research and Forecasting with Chemistry (WRF-Chem) model for four one-month periods (January, April, July, and October). Two emissions scenarios were conducted with the BASE case having emissions of 2013 and the ER60 case decreasing coal-fired power plants emissions to the standards of gas power plants. Model results from the BASE case were first evaluated through a comparison with observational data collected at 47 urban sites across China, which showed mean fractional bias in the range of –27% to 10% and mean fractional error in the range of 15% to 36% depending on chemical species, suggesting the reasonable performance of the modeling system. The ER60 simulation revealed potential decreases of 8%, 40% and 20% in annual concentrations of PM2.5, SO2 and NO2, respectively, in eastern China should the emissions from coal-fired power plants be reduced to the standards of gas power plants. Stringent control plans for coal-fired power plants as well as for other major emission sources are needed to improve urban air qualities across China.

Keywords: Urban air quality; Emission control; Numerical study; Fine particulate matter; Sulfur dioxide; Nitrogen dioxide.

INTRODUCTION

China has experienced serious air pollution in the recent decades due to the rapid economic growth and urban expansion. Severe haze has been frequently formed in many regions of China, to which fine particulate matter (PM2.5) is a major contributor (Cheng et al., 2013; Wang et al., 2014). In addition to primary emissions, PM2.5 formed in the atmosphere from reactions between gaseous precursors such as SO2, NOx, NH3 and volatile organic compounds (VOCs) constitutes a large fraction of the total PM2.5 mass in Chinese megacities (Huang et al., 2014).

The energy production sector, mainly including coal combustion from boilers and power plants in China, has attracted considerable attention because it contributes large proportions to the ambient concentrations of SO2 and NOx (Chen et al., 2014). In 2014, an energy-saving and environmental protection concept, called ultralow emission, was proposed for coal-fired power plants in China. Over 99.7% of PM2.5 can be captured by available ultralow emission techniques such as fuel gas desulfurization, retrofitted electrostatic precipitation, and wet electrostatic precipitation (Sui et al., 2016). These techniques are currently more economical to operate than new energy (gas, wind, and solar power) power plants (Shuai et al., 2015). The Chinese state council plans to fully upgrade coal-fired power plants nationwide with ultralow emission equipment. Coal-fired power plant emissions should achieve the level of gas power plant emissions before 2020 (National Development and Reform Commission et al., 2014). The efficacy of these policies has implications for both the government and the public. Quantitative assessment of the relationship between air quality benefits and emission reductions from coal-fired power plants has not been sufficiently investigated on a national scale.

Chemical transport models are useful tools in quantifying atmospheric pollutants sources and fates and providing information for assessing the subsequent impacts of these pollutants on ecosystem and human health. These models are also useful in conducting sensitivity tests on different scenarios of emission controls (Kukkonen et al., 2012; Kheirbek et al., 2014). The Weather Research and Forecasting with Chemistry (WRF-Chem) model (Grell et al., 2005), a regional online coupled meteorological and chemical model, has been evaluated and applied extensively.

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METHODOLOGY

The Modeling System

The WRF-Chem model is an Eulerian model that simultaneously simulates air quality and meteorological components using the same transport scheme, grid setting, physics scheme, and time step for sub-grid transport. In this study, the gas mechanism CBMZ (Chemical Bond Mechanism Version Z) (Zaveri and Peters, 1999) and the aerosol mechanism MOSAIC (Model for Simulating Aerosol Interactions and Chemistry) (Zaveri et al., 2008) were chosen for model simulations. Detailed model configurations were described in our previous study (Ni et al., 2018). The computational domain (Fig. 1) covered the Chinese mainland (20–47°N, 98–125°E) with 90 (longitudinal) and 100 (latitudinal) grid points at a horizontal resolution of 30 km on the Lambert projection, centered at 34°N, 111°E (central China). A total of 31 terrain-followed sigma vertical layers were selected with finer vertical resolutions near the surface and model top at 100 hPa. To reduce computational costs, four representative months (January, April, July, and October) were selected to reflect the seasonal characteristics. For each month, an extra of 7 days at the beginning of the simulations was used as the spinning-up period to alleviate the impact from the initial conditions.

The terrain and land-use data were obtained from the US Geological Survey database (Brown et al., 1993). The meteorological initial and boundary conditions were provided by the US National Centers for Environmental Prediction global objective final analysis data (http://rda.ucar.edu/data sets/ds083.2/). The chemical initial and boundary conditions were downscaled from the simulation results of MOZART4 (model for ozone and related chemical tracers, version 4) (Emmons et al., 2010).

Anthropogenic emissions were based on the Multi-resolution Emission Inventory for China (MEIC; 0.5° × 0.5° resolution, http://www.meicmodel.org). There are five sectors in MEIC emission inventory including power plants, industry, residence, transportation and agriculture. Available emission species include CO, NOx, SO2, VOCs, NH3, BC, OC and primary PM2.5. Power plant emission was used with a unit-based emission inventory including a majority of coal-fired power plants across China (validated by Liu et al., 2015). Annual total emissions were formatted into hourly model-ready emissions by applying temporal profiles based on Wang et al. (2011a). Biogenic emissions were estimated using MEGAN (model of emission of gases and aerosol from nature) (Guenther et al., 2006). Dust emissions were calculated on-line from land-use information (mainly soil moisture and erodible fraction) and meteorological fields.

Simulation Scenarios

The WRF-Chem modeling system was used to investigate air quality changes in response to emission reductions under various control scenarios. Model simulations were conducted for the BASE and the ER60 cases with the former representing the standard Chinese anthropogenic emissions in the year of 2013 and the latter representing designed reduced emissions as detailed below. Model performance was first evaluated in the BASE case using available measurements of PM2.5, SO2 and NO2 data collected at 47 national air quality monitoring sites.

Fig. 1. Topographic map of the study domain (black box) with air quality monitoring sites (black points) in China. The red triangle denotes the Hangzhou site.
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(\url{http://www.stats.gov.cn}, Fig. 1). These sites are situated in metropolitan areas across China and are representative of fast growing urban areas, and thus were also chosen for air-quality analysis under the two emission scenarios. Pearson’s correlation coefficient (R), mean fractional bias (MFB) and mean fractional error (MFE) were calculated (Boylan and Russell, 2006). These two metrics can filter extreme fluctuations in PM$_{2.5}$ and serve as less stringent criteria at low concentrations to account for high uncertainties near detection limits.

The newly established coal-fired power plant emission standards of PM, SO$_2$ and NO$_X$ are limited to 30 mg m$^{-3}$, 100 mg m$^{-3}$ and 100 mg m$^{-3}$, respectively (Ministry of Environmental Protection, 2011), and the proposed gas power plant emission standards are limited to 10 mg m$^{-3}$, 35 mg m$^{-3}$ and 50 mg m$^{-3}$, respectively (National Development and Reform Commission et al., 2014). To reach the national gas power plant emission standards, PM$_{2.5}$, SO$_2$ and NO$_X$ emissions from coal-fired plants should decrease by approximately 67%, 65% and 50%, respectively, which is referred to as the ER60 case in this study. Air quality benefits under the ER60 scenario were assessed in terms of seasonal and spatial reductions of air pollutants surface concentrations relative to those from the BASE scenario.

RESULTS

Model Performance Evaluation

Annual mean concentrations from the model output were calculated using the available four one-month simulation results and were compared with annual mean of measurements at the 47 sites. r-test ($\alpha = 0.05$) was performed to test the statistical significance and *R indicates statistical significance at 95% confidence level (Fig. 2). The model reasonably reproduced the observed air pollutants concentrations during the study period, as seen from the statistically significant correlations. MFB and MFE of PM$_{2.5}$ (Figs. 2(a) and 2(d)) were generally within the criteria (MFB: ± 30%, MFE: 50%) recommended by Boylan and Russell (2006). If the same criteria for PM$_{2.5}$ were also used for SO$_2$ and NO$_X$, these criteria were also met. Furthermore, the time series and statistical metrics for air pollutants (Figs. 2(d)–2(f)) were also generated for the urban site in the city of Hangzhou, which shows that the model simulations not only captured the seasonal and daily variations, but also yielded satisfactory statistical metrics (MFB and MFE). Comparable performance has also been found in previous studies (e.g., Zhang et al., 2014; Guo et al., 2016; Ni et al., 2018).

![Fig. 2. Comparison and linear regression of modeled air pollutants concentrations from the Base case against measurements: (a–c) annual concentration at 47 monitoring sites in 2013, and (d–f) daily concentration at the Hangzhou site during the four one-month periods.](image-url)
Figure 3. Modeled monthly concentrations (µg m⁻³) of air pollutants at ground level in 2013 across China.

Characteristics of Air Pollutants Distributions

Spatial distributions of air pollutants concentrations showed different seasonal patterns as shown in Fig. 3. Large city clusters in the North China Plain (NCP) and the Yangtze River Delta (YRD) were determined to be the most polluted regions during October and January. PM₂.₅, SO₂, and NO₂ followed similar distribution patterns. Stable weather conditions in winter (January) are conducive for pollutant accumulation of local emissions (Zhang et al., 2014). By contrast, the relatively low concentrations of air pollutants in April and July are associated with the summer monsoon season (Zhao et al., 2010), which brings in clean marine air from the western Pacific and dilutes the pollution. Wet scavenging of PM₂.₅ and weak photochemical activity caused by associated clouds and precipitation can also reduce aerosol concentrations. PM₂.₅ concentration was notably high (> 200 µg m⁻³) in Mongolia regions, mostly because of natural dust aerosols from desert land-cover (Chen et al., 2003).

Site-averaged PM₂.₅ components generated from model results are shown in Fig. 4. On annual average, secondary inorganic aerosols (sulfate, nitrate, and ammonium) were estimated to contribute 27% of the total PM₂.₅ mass. Such a result is within the range of the observations made in the past decade as reviewed in Tao et al. (2017), which showed 25–48% contributions in various seasons and across China. Higher percentage contributions were found in polluted episodes such as the one occurred in January 2013 (Huang et al., 2014; Wang et al., 2014). In addition, PM₂.₅ components varied with season and region. Tao et al. (2017) summarized that the highest seasonal average contributions of secondary inorganic aerosols to PM₂.₅ were observed in summer (in most of the northern cities) and winter, which was mostly reproduced in model results of the present study. Thus, secondary chemical transformation from anthropogenic precursors is an important contributor to PM₂.₅ pollution in the atmosphere. Considering that the coal-fired power plants are important sources of the gaseous precursors (Chen et al., 2014), substantial emission reductions from these sources are needed in order to alleviate PM₂.₅ pollution in many regions of China.

Assessment of Air Quality Benefits

The modeling results from the ER60 case simulations were compared with those from the BASE case simulation. Fig. 5 illustrates that substantial reductions of pollution can
Fig. 4. Fractions of major PM$_{2.5}$ components averaged for the 47 monitoring sites in 2013 China. “Others” in the legend contains BC, OC, chlorine, sodium, salt, dust, etc.

Fig. 5. Modeled monthly reductions in air pollutant concentrations ($\mu$g m$^{-3}$) at ground level in 2013 across China after coal-fired power plant emissions being reduced to the level of gas power plant emissions (BASE minus ER60).
be achieved over the North China Plain and Yangtze River Delta regions if the nationwide emission standards of coal-fired power plants meet those of gas power plants. Although such level of air pollutant reductions can ease severe haze pollution to some extent, annual PM$_{2.5}$ concentrations in many regions were determined to remain far above the national standard of 35 µg m$^{-3}$. More comprehensive emission control measures such as industrial upgrading, vehicle limiting, or cleaner energy transferring are required (Tao et al., 2017).

Fig. 6 summarizes the site-averaged air pollutant changes from the BASE scenario to the ER60 scenario. Pollutant reductions varied by season and chemical species. Annual average PM$_{2.5}$, SO$_2$, and NO$_2$ surface concentrations in China were reduced by 8%, 40% and 20%, respectively. SO$_2$ and NO$_2$ were reduced more than PM$_{2.5}$, because coal combustion from coal-fired power plants contributes more SO$_2$ and NO$_2$ than PM$_{2.5}$. Secondary inorganic aerosols (sulfate, nitrate, ammonium), which are formed primarily through atmospheric oxidation of SO$_2$ and NO$_2$, were reduced more than the other aerosols. This is consistent with low pollutant reductions during winter (January) than summer (July) because low temperatures reduced the formation of secondary aerosols. Although ultralow emission techniques do not apply to NH$_3$ emissions, ammonium decreased by 14% as well due to its association with sulfate and nitrate through secondary aerosol formation (Wang et al., 2011b).

CONCLUSIONS

This study provides some insights into the potential air quality benefits of national ultralow emission policy at coal-fired power plants. If primary emissions of PM$_{2.5}$, SO$_2$ and NO$_x$ were reduced by 67%, 65% and 50%, respectively, annual average PM$_{2.5}$, SO$_2$ and NO$_2$ surface concentrations in China would be reduced by 8%, 40% and 20%, respectively, suggesting that ultralow emission techniques at coal-fired power plants may improve the air quality in China. The emission policy is most efficient for SO$_2$ due to the large SO$_2$ emissions from power plants. A 67% reduction in gas power plants SO$_2$ emissions would yield a 40% reduction in the large-scale annual SO$_2$ concentration. More reductions were found for secondary inorganic aerosols (sulfate, nitrate, ammonium) than the other aerosols. More reductions were also found in summer than in the other seasons for secondary inorganic aerosols. This study suggests that only reducing emissions from coal-fired power plants is not enough in alleviating serious PM$_{2.5}$ pollution across China. Multiple emission control policies are needed, for example, providing cleaner energy for rural areas for daily life needs, controlling biomass burning activities, reducing traffic emission in urban centers, controlling agricultural emissions, and abating soil dust events especially those originated from the Mongolia regions.

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