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Model assessment of atmospheric pollution control schemes for critical emission regions

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HIGHLIGHTS

- FLEXPART was used in tracking sensitive emission regions.
- Full and sensitive HuaBei and Beijing emission regions were defined.
- Twelve controlling scenarios were modeled and compared using Models-3/CMAQ.
- Earlier and joint emission control schemes assure better overall air quality.
- Reducing emissions in sensitive emission regions can improve control efficiency.

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ABSTRACT

In recent years, the atmospheric environment in portions of China has become significantly degraded and the need for emission controls has become urgent. Because more international events are being planned, it is important to implement air quality assurance targeted at significant events held over specific periods of time. This study sets Yanqihu (YQH), Beijing, the location of the 2014 Beijing APEC (Asia–Pacific Economic Cooperation) summit, as the target region. By using the atmospheric inversion model FLEXPART, we determined the sensitive source zones that had the greatest impact on the air quality of the YQH region in November 2012. We then used the air-quality model Models-3/CMAQ and a high-resolution emissions inventory of the Beijing-Tianjian-Hebei region to establish emission reduction tests for the entire source area and for specific sensitive source zones. This was achieved by initiating emission reduction schemes at different ratios and different times. The results showed that initiating a moderate reduction of emissions days prior to a potential event is more beneficial to the air quality of Beijing than initiating a high-strength reduction campaign on the day of the event. The sensitive source zone of Beijing (BJ-Sens) accounts for 54.2% of the total source area of Beijing (BJ), but its reduction effect reaches 89%–100% of the total area, with a reduction efficiency 1.6–1.9 times greater than that of the entire area. The sensitive source zone of Huabei (HuaB-Sens.) only represents 17.6% of the total area of Huabei (HuaB), but its emission reduction effect reaches 59%–97% of the entire area, with a reduction efficiency 4.2–5.5 times greater than that of the total area. The earlier that emission reduction measures are implemented, the greater the effect they have on preventing the transmission of pollutants. In addition, expanding the controlling areas to sensitive provinces and cities around Beijing (HuaB-sens) can significantly accelerate the reduction effects compared to controlling measures only in the Beijing sensitive source zone (BJ-Sens). Therefore, when enacting emission reduction schemes, cooperating with surrounding provinces and cities, as well as narrowing the reduction scope to specific sensitive source zones prior to unfavorable meteorological conditions, can help reduce emissions control costs and improve the efficiency and maneuverability of emission reduction schemes.

1. Introduction

In recent years, China has hosted several international events

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during which air quality was very well controlled. This suggests that taking corrective measures to reduce emissions can minimize unfavorable meteorological impacts on air quality. Scientists have conducted numerous analyses and assessments on air quality and ambient meteorological conditions before, during, and after large-scale events. Chen et al. (2010) combined an air quality forecasting model with a pollution source tracking method. They quantified the contribution of emissions from urban sources in the Pearl River Delta to different regional and local pollutant concentrations measured at monitoring stations in Guangzhou during the 2006 Guangzhou Asian Games. They emphasized the necessity for joint emissions controls. Through a numerical simulation, Street et al. (2007) quantitatively presented the pollutant contributions of the provinces and cities surrounding Beijing to the total pollutant concentration in Beijing. They suggested that a collective effort between Beijing and its surrounding provinces and cities was necessary to ensure air quality during the 2008 Olympic Games. Wu et al. (2010a) used meteorological field displacement modeling to conclude that the sharp decrease in PM_{10} during the Beijing Olympic Games was primarily due to a decrease in the number of emission sources. Chen et al. (2013) illustrated the important role of meteorological conditions on air quality during the 2010 EXPO in Shanghai China, when 98.4% of the Grade II national air quality standard (see Table 1 in the Supplementary materials) was met. They analyzed air quality data and meteorological conditions over the ten years (2001–2010) prior to the 2010 EXPO. Huang et al. (2013) analyzed the impacts of seasonal changes, sand, dust, and related management techniques on air pollution in Shanghai. Li et al. (2012) carefully analyzed the variation in air quality characteristics and meteorological conditions during the 2010 Guangzhou Asian Games. In addition, Xie et al. (2014) assessed the effect of environmental control measures during the 2014 Nanjing Youth Olympic Games. These studies have provided valuable references for assessing air quality during specific periods, as well as suggestions for improving the atmospheric environment.

Meteorological diffusion conditions and pollution source emissions are two key elements that influence local and regional air quality. When weather circulation patterns disallow pollutant diffusion, emission control measures can be very effective at lowering pollutant concentrations, thus meeting air quality standards. In addition to local pollution sources, the pollutant concentrations in a city or region are affected by the emissions and transmissions from surrounding areas (Jaffe et al., 1999; An et al., 2007; Chen et al., 2007; Zhou et al., 2010; An et al., 2012). Moreover, due to the variability in atmospheric circulation, major emission sources that impact the air quality of a specific region cannot always be fixed. Therefore, it is necessary to identify the critical emission regions (sensitive source zones) that most seriously affect the pollutant concentrations of specific regions during specific periods. Identifying these zones is the basis for establishing effective emission control measures and is also a key for improving the efficiency of control schemes by reducing costs.

The 2014 APEC Summit was held in Yanqihu (YQH), in the Huairou District of Beijing during 10–11 November 2014. In this study, we implement the Lagrangian particle dispersion model FLEXPART (FLEXible PARTicle dispersion model) to track the critical source areas of YQH based on the meteorological conditions in November 2012. In addition, we utilize the Models-3/CMAQ (Community Multi-scale Air Quality) modeling system and quantitatively assess the emission reduction effects of initiating the reduction of emission sources at different percentages and different times. This assessment is conducted over the entire source area and focuses on sensitive source zones. Our goal is to determine effective pollution reduction measures when meteorological conditions do not promote pollutant diffusion. This paper contains four sections. Section 2 introduces the data and methodology. Section 3 displays the comparative results of the model sensitivity tests. Section 4 presents the major conclusions of the study.

2. Data and methods

2.1. Introduction to FLEXPART model

The FLEXPART model is a Lagrangian particle dispersion model (LPDM) developed by the Norwegian Institute for Air Research (NILU) (Stohl et al., 2005). By calculating the trajectories of a large number of particles released by point, line, plane, or bulk sources, the model can describe the processes of long-distance mesoscale transmission, diffusion, dry and wet deposition, and radiation attenuation of tracers in the atmosphere. This model can simulate the diffusion of tracers through forward-time calculations and can also determine the distribution of potential source areas through backward calculations (Seibert, 2004). In fact, the FLEXPART model has been successfully applied globally (Stohl, 1996; Stohl et al, 1998; Stohl and Trickl, 1999; Stohl et al, 2003; Hirdman et al., 2010; Foy et al., 2006). At present, there are at least 25 research groups from 14 countries engaged in applied research programs that adopt this model (Stohl et al., 2005).

The core of the FLEXPART model focuses on the source–receptor relationship of air pollutants. The pollutant is emitted from a "source" and observed at a "receptor" site. Through studying the processes of horizontal transmission, diffusion, convection, dry and wet deposition, radiation attenuation, and first-order reactions of pollutants, we can obtain grid pollution concentrations (forward simulations) or grid residence times (also called sensitive coefficients, mark functions, or backward simulations), as well as temporal variations in the processes.

According to the characteristics of the study, this paper sets the following parameters for the FLEXPART model. The direction of the model simulation is backward. The source of model emissions is a point source, i.e., the specific spot chosen for this study is YQH (40.40°N, 116.68°E) in Huairou County, Beijing. Fifty thousand particles are released every 3 h, and it takes 15 days to complete a backward simulation. The model outputs residence time, also known as the sensitivity coefficient or mark function. The units are set as s m^3 kg^{-1}, referring to the residence time of the unit mass of polluting gases at horizontal grids with a resolution of $1 \times 1°$. It is noteworthy that the "source of emissions" is not an actual "source" but the distribution of the primary sources and potential source areas of the air masses that influence the local concentrations.

2.2. Introduction to meteorological-chemical model system and data

The Models-3/CMAQ modeling system was developed by the U.S. Environmental Protection Agency (EPA) in the 1990s. It has been used extensively in the theoretical study and operational prediction of atmospheric pollution problems, including photochemical smog, regional acid deposition, and pollution by atmospheric particulate matters at regional and city scales. We use a CB-IV scheme for the gas-phase chemistry, a RADM scheme for the aqueous-phase chemistry, and other schemes (Wu et al., 2014).

In this study, the NCAR/Penn State Mesoscale Model (MM5) is utilized to provide meteorological fields. We select an MRF scheme for the boundary layer process, a Grell scheme for convective motion, and a cloud-cooling scheme for radiation (An et al., 2007). The emission source processing system SMOKE, which was developed by the Microelectronics Center of North Carolina (MCNC), U.S., is used to process point, area, and transportation sources, translating the emissions inventory into the grid emission data required by the