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Modelling study of boundary-layer ozone over northern China - Part II: Responses to emission reductions during the Beijing Olympics

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ABSTRACT

The implementation of emission reduction measures during the Olympics provided a valuable opportunity to study regional photochemical pollution over northern China. In this study, the fifth-generation Pennsylvania State University/National Centre for Atmospheric Research Mesoscale Model and Community Multiscale Air Quality model system was applied to conduct two sets of modelling analyses of the period from July 20 to September 20, 2008, to illustrate the influences of emission reduction measures on regional photochemical pollution over northern China during the Beijing Olympics. The results indicated that the implementation of emission control measures decreased the concentrations of ozone (O_3) precursors, namely nitrogen oxide (NOx) and volatile organic compounds (VOCs), throughout the boundary layer. The concentrations of these compounds were reduced by 45% in the central urban area of Beijing at the ground level. Although the average O_3 concentration in the central urban area increased by more than 8 ppbv, the total oxidant concentration decreased significantly by more than 5 ppbv. Greater O_3 concentrations mainly occurred during periods with weak photochemical reactions. During periods of strong photochemical production, the O_3 concentration decreased significantly due to a weakening vertical circulation between the lower and upper boundary layer. Consequently, the number of days when the O_3 concentration exceeded 100 ppbv decreased by 25% in Beijing. The emission control measures altered the sensitivity of the regional O_3 production. The coordinated control region of NOx and VOCs expanded, and the control region of VOCs decreased in size. The reduction of non-point-source emissions, such as fugitive VOCs and vehicles, was more useful for controlling regional photochemical pollution over northern China.

1. Introduction

The Summer Olympic Games are one of the most influential and globally comprehensive sporting events. From the 1940s to the 1970s, London, Helsinki, Melbourne, Rome, Tokyo, Mexico City, Munich and Montreal each hosted the Summer Olympic Games. During this period, the economies of these countries developed rapidly, but people lacked adequate awareness of environmental protection. Thus, no special measures were adopted during the Olympic Games held during this period to protect the atmosphere and environment. Since the 1980s, and with global environmental protection progress, the Olympics organization has gradually began considering the environment in addition to sports activities.

As the political, economic and cultural centre of China, Beijing gained the right to host the 2008 Summer Olympic Games in 2001. Compared with other cities that had previously hosted the Olympics, a considerable gap in air quality occurred during the Beijing Olympics. With high concentrations of inhalable particulate matter (PM_{10}) and ozone (O_3), Beijing experiences continuous atmospheric pollution (Tang et al., 2009, 2012; Xin et al., 2010; Wang et al., 2015). From the end of 1998 to the opening ceremony of the 2008 Olympics, the Beijing Municipal Government successively promulgated and implemented fourteen stages of control measures for air pollution and effectively suppressed air pollution in Beijing. However, because of the severity of the regional air pollution in Beijing, the promised air quality was not sufficiently met following the implementation of the control measures (Streets et al., 2007).

To fulfil the promise proposed during the application for the Olympics, the State Council approved the decision to establish the Coordinate Group for Air Quality Protection Work in Beijing during the 2008 Olympics to strengthen cooperation with peripheral provinces, cities and the

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autonomous region. This group was responsible for organizing and coordinating the Air Quality Safeguard Research of Beijing during the 29th Olympic Games - Measures of Beijing and Air Quality Safeguards Research of Beijing during the 29th Olympic Games - Measures for the Surrounding Provinces, City and Autonomous Region of Beijing (MEPPRC and BMG, 2007a, 2007b). Thus, based on the pollution control measures proposed by the relevant departments of the five provinces and cities in northern China, a research report on the Air Quality Safeguards Research of Beijing during the 29th Olympic Games - Measures of Five Provinces, Cities and Autonomous Region in Northern China was summarized and compiled (MEPPRC and BMG, 2007c).

Based on this research report, the five provinces, cities and autonomous region in northern China jointly investigated the reduction of pollutants from atmospheric emission sources during the Olympics. During this period, researchers performed many observational studies. Studies of the emission sources indicated that the vehicle flow-rate was reduced by 32.3% by limiting which vehicles were allowed on the roads based on whether they had an odd or even plate number during the Olympics (Wang and Xie, 2009). The levels of volatile organic compounds (VOCs), monoxide (CO), nitrogen oxide (NOx) and PM_{10} that were discharged by motor vehicles were reduced by 55.5, 56.8, 45.7 and 51.6%, respectively (Zhou et al., 2010); and the decline of road dust was particularly significant (Fan et al., 2009). At urban and rural stations in Beijing, the contributions of motor vehicles to organic carbon (OC) emissions decreased by 30 and 24%, respectively, and the contributions of coal combustion decreased by 57 and 7%, respectively (Guo et al., 2013).

Because of the effective implementation of emission reduction measures, the nitrogen dioxide (NO_2) concentrations in the troposphere, the sulphur dioxide (SO_2) column concentrations in the boundary layer and the CO concentrations at 700 hpa in the urban area of Beijing decreased by 40–59, 13 and 12%, respectively (Mijling et al., 2009; Witte et al., 2009). The concentrations of near-surface gaseous pollutants (NOx, CO, SO_2 and VOCs) decreased significantly in the urban area of Beijing (Chou et al., 2011; Okuda et al., 2011; Wang et al., 2010a; Wang et al., 2009a; Wang and Xie, 2009; Xu et al., 2016), which also caused the CO and SO_2 concentrations at Miyun station in the leeward region of Beijing to decrease significantly (Wang et al., 2009d). In addition, the VOC emissions during the Olympics decreased by 45% compared to June, and the emissions from motor vehicles, solvent use, industrial processes and fugitive uses decreased by 66, 48, 15 and 75%, respectively (Su et al., 2011). In particular, aromatic hydrocarbons with strong chemical activity decreased significantly, and benzene, toluene, ethylbenzene and xylenes (BTEX) decreased by 47–64% (Liu et al., 2009). However, no significant changes were observed in the concentrations of alkanes and benzene with long lifetimes (Wang et al., 2010b). Moreover, formaldehyde, aldehyde, methyl ethyl ketone and methyl alcohol were significantly reduced by 12.9, 15.8, 17.1 and 19.6%, respectively, and the concentrations of acetone did not significantly change during the Olympics (Liu et al., 2015). Noticeably, the formaldehyde concentrations peaked twice during the rush hours, indicating that motor vehicles remained the main sources of formaldehyde precursors (Li et al., 2010).

The significant decrease in gaseous pollutants also caused a change in the particulate matter concentration (Xu et al., 2016). Studies based on laser radars have indicated that the light extinction coefficient for aerosols decreased by 42.3% during the Olympics compared to the same time period in 2007 in the urban area of Beijing (Yang et al., 2010). The optical thickness of aerosol, which was observed by satellites, also decreased considerably (Cermak and Knutti, 2009; Wang et al., 2009a). Moreover, a significant difference was observed in the variations of particulate matter with different particle sizes. In the urban area of Beijing, the PM_{10} and total suspended particulate (TSP) concentrations decreased significantly, but the reduction in fine particulate matter ($PM_{2.5}$) was not significant (Schleicher et al., 2012; Schleicher et al., 2011; Wang and Xie, 2009; Wang et al., 2009b). The water soluble Ca^{2+} and SO_4^{2-} ions decreased the most in the TSPs and PM_{10}, and no obvious decreases in NH_4^+ and NO_3^- were observed (Norra et al., 2016; Okuda et al., 2011; Schleicher et al., 2012). The most significant decreases in the $PM_{2.5}$ fraction were observed for elements related to human activities, such as S, Cu, As, Cd, Pb and black carbon (BC) (Fan et al., 2009; Norra et al., 2016; Schleicher et al., 2012; Wang et al., 2009d). The toxic substances in the particulate matter, namely, polycyclic aromatic hydrocarbons (PAHs), also exhibited a large decline (Fan et al., 2009; Ma et al., 2011; Norra et al., 2016; Schleicher et al., 2012), and the magnitude of the decline in PAHs was the largest for PAHs with between five and seven rings (Okuda et al., 2011). Moreover, by comparing the vertical profiles of the atmospheric extinction coefficient before and during the Olympics Games, the atmospheric extinction coefficient exhibited the most significant decrease from 0.5 to 1.5 km, indicating that the amount of PM_{10} from transportation decreased by 36.6% during the Olympic Games and demonstrating the effectiveness of the regional coordinated control measures (Yang et al., 2010).

Although the concentrations of particulate matter and primary gaseous pollutants decreased during the Olympics, another important secondary pollutant, O_3, increased (Chou et al., 2011; Wang and Xie, 2009). However, although the O_3 concentration increased, the total oxidant (Ox), total reactive nitrogen (NOy) and NOz (NOy-NOx) concentrations in the atmosphere decreased (Chou et al., 2011), which caused the O_3 concentration at the Miyun station in the leeward region of Beijing to decrease significantly and indicated that reducing the emissions in an urban area can affect a larger area (Wang et al., 2009c). Because of the emission reduction effects, the production of O_3 was controlled by NOx during the Olympics and by VOCs before and after the Olympics (Chou et al., 2011; Witte et al., 2011; Xing et al., 2011).

Although previous detailed and focused studies have been conducted, these studies contain the following drawbacks: (1) they excessively focus on the Beijing area with insufficient studies of the surrounding area; (2) most previous studies discuss only the distribution of pollution near the ground and ignore the characteristics of the air pollutants in the upper boundary layer; and (3) the emission reduction measures proposed in most previous studies are targeted at specific chemical species, such as NOx and VOCs, without considering a certain type of source. To compensate for these shortcomings in studies of O_3 pollution over northern China, we considered the period of emission reduction during the Olympics and used a large amount of observational data to validate a numerical model system. Our analysis illustrates the effectiveness of the control strategies implemented during the Olympics, deeply explores the influences of emission control measures on the characteristics of the O_3 distribution and its budget, and proposes additional operational control strategies for photochemical pollution over northern China.

2. Methodology

2.1. Air quality model simulation and observations

Strict emission control measures were implemented before and after the 29th Olympic Games held in Beijing in August–September 2008. Therefore, we derived a list of emissions sources under different control measures based on the measures and strengths of emissions control. Afterwards, the period of June–September 2008 was divided into the following four emission control implementation stages: June, July 1–19, July 20–September 20 and September 20–30. The emission control measures had not yet been implemented over northern China in June 2008, which was two months before the opening ceremony of the Olympics. The periods of July 1–19 and September 20–30 were transition periods during which emissions measures were implemented and suspended, respectively. These three periods were not discussed because the variations of emission sources during these periods were relatively complicated. The Olympics and Paralympics took place from July 20 to September 20, 2008, which is a relatively long period. Because the emission levels were essentially stable once the emission sources were