Environ. Sci. Technol. **2010,** *44,* 2490–2496

Quantifying the Air Pollutants Emission Reduction during the 2008 Olympic Games in Beijing

SHUXIAO WANG, MENG ZHAO, JIA XING,
YE WU, YU ZHOU, YU LEI, KEBIN HE,
LIXIN FU, AND JIMING HAO*

Department of Environmental Science and Engineering, and State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), Tsinghua University, Beijing 100084, China

Received September 23, 2009. Revised manuscript received December 27, 2009. Accepted March 2, 2010.

Air quality was a vital concern for the Beijing Olympic Games in 2008. To strictly control air pollutant emissions and ensure good air quality for the Games, Beijing municipal government announced an "Air Quality Guarantee Plan for the 29th Olympics in Beijing". In order to evaluate the effectiveness of the guarantee plan, this study analyzed the air pollutant emission reductions during the 29th Olympiad in Beijing. In June 2008, daily emissions of SO_2, NO_X, PM_{10}, and NMVOC in Beijing were 103.9 t, 428.5 t, 362.7 t, and 890.0 t, respectively. During the Olympic Games, the daily emissions of SO_2, NO_X, PM_{10}, and NMVOC in Beijing were reduced to 61.6 t, 229.1 t, 164.3 t, and 381.8 t −41%, 47%, 55%, and 57% lower than June 2008 emission levels. Closing facilities producing construction materials reduced the sector's SO_2 emissions by 85%. Emission control measures for mobile sources, including high-emitting vehicle restrictions, government vehicle use controls, and alternate day driving rules for Beijing's 3.3 million private cars, reduced mobile source NO_X and NMVOC by 46% and 57%, respectively. Prohibitions on building construction reduced the sector's PM_{10} emissions by approximately 90% or total PM_{10} by 35%. NMVOC reductions came mainly from mobile source and fugitive emission reductions. Based on the emission inventories developed in this study, the CMAQ model was used to simulate Beijing's ambient air quality during the Olympic Games. The model results accurately reflect the environmental monitoring data providing evidence that the emission inventories in this study are reasonably accurate and quantitatively reflect the emission changes attributable to air pollution control measures taken during the 29th Olympic Games in 2008.

Introduction

Beijing, China's capital, is one of the world's largest metropolises with a population of more than 16.9 million and a vehicle fleet of more than 3.5 million (*1*). High levels of coal consumption, thousands of active construction sites, and rapid increases in the vehicle population have resulted to high emissions of particulate matter, sulfur dioxides (SO_2), nitrogen oxide (NO_X), and non-methane volatile organic compounds (NMVOCs) in Beijing (*2*). In 2000, the annual average concentrations of particulate matter with diameters less than or equal to 10 μm (PM_{10}), SO_2, and NO_2 were 162 $\mu g/m^3$, 71 $\mu g/m^3$, and 71 $\mu g/m^3$, respectively (*3*). Research has shown that concentrations of particulate matter with diameters less than or equal to 2.5 μm ($PM_{2.5}$) are also very high, with average daily concentrations between 2000 and 2005 ranging from 91 to 169 $\mu g/m^3$ (*4–8*). Studies indicate that high concentrations of ozone (O_3) exceeding China's grade II National Ambient Air Quality Standard of 200 $\mu g/m^3$ were observed from June to September between 2000 and 2005 (*4, 9, 10*). Because of these air quality challenges, the international community raised serious concerns about the air quality in Beijing for the 2008 Olympic Games since Beijing won the bid to host the Olympic Games in 2001.

The Beijing Municipal Government has implemented numerous air pollution control measures since 2000. Heavy-polluting industrial facilities (e.g., oil refineries and steel-making factories) were relocated, numerous coal-fired boilers and domestic stoves were modified to use natural gas, more stringent local emission standards for coal-fired boilers were implemented, and older vehicle fleets were replaced with newer, cleaner fleets. These measures have increased the number of air quality attainment days in the city every year, from 177 days in 2000 to 246 days in 2007 (http://www.bjepb.gov.cn/). During the same period, the ambient concentrations of SO_2, NO_X, and PM_{10} have decreased 26.6%, 7.0%, and 10.3%, respectively. However, the PM_{10} and O_3 pollution in Beijing still posed a critical challenge to the promise of clean air during the Olympic Games. Several studies were conducted to provide scientific guidance to the government on effective air pollution control options for the Olympic Games. Emissions inventories were developed to identify the most important emission sources (*2, 11, 12*). Wang et al. (*13*) and Cheng et al. (*14*) demonstrated that four-day traffic restrictions in Beijing during the Sino-African Summit in early November 2006 resulted in significant temporary reductions in concentrations of NO_X and particulates in the city, but the effect on surface ozone was not characterized. Streets et al. (*15*) and Wang et al. (*16*) estimated that, on average, 40% of PM_{10} and 34% of $PM_{2.5}$ concentrations in Beijing can be attributed to regional emissions outside of Beijing. Streets et al. (*15*) also estimated that 35−60% of O_3 concentrations during high-O_3 episodes can be attributed to regional emissions of NO_X and NMVOCs outside Beijing. The studies hypothesized that better air quality could only be attained during the Olympic Games by placing effective emission controls on both emission sources in Beijing and the surrounding regions. Wang et al. (*10*) analyzed the intraseasonal differences in CO and O_3 measured at a rural Beijing monitoring site-Miyun- and suggested that emissions should be controlled when meteorological conditions are likely to be relatively cloud-free. Wang et al. (*17*) calculated the emissions of primary air pollutants from coal-combustion and simulated the impacts of coal combustion in each district and each sector on air quality in Beijing.

To ensure good air quality during the Olympic Games (August 8−24, 2008) and the Paralympic Games (September 9−17, 2008), the Ministry of Environmental Protection of the People's Republic of China and the Beijing Municipal Government jointly developed air quality guarantee measures for the 29th Olympic Games, which were implemented to reduce emissions in both Beijing and surrounding areas (http://www.gov.cn/xwfb/2008-02/27/content_903668.htm). These emission restrictions offer an invaluable opportunity to test our understanding of air pollutant emissions, atmospheric chemistry, and physics in Beijing and the surrounding area. This paper aims to provide a scientific assessment of

---

* Corresponding author phone: +86-10-62782195; fax: +86-10-62773650; e-mail: hjm-den@tsinghua.edu.cn.

10.1021/es9028167

how air pollution measures affected emissions and air quality during the Olympic Games and to help explore long-term mechanisms for air quality improvement in Beijing.

Methodology

In this study, we first estimated air pollutant emissions “before the Olympic Games” (June 2008) and then calculated the emissions “during the Olympic Games” (from July to August 2008) considering the temporary air pollution control measures implemented. Finally we used the CMAQ model to validate the emission estimates during the Olympic Games.

Emission Inventory Model. Anthropogenic emissions were estimated for major chemical species including SO_2, NO_X, NMVOC, and PM_{10}. To provide a high resolution the study used a bottom-up approach where possible. Anthropogenic emissions in Beijing before the Olympic Games are aggregated from a bottom-up investigation of thousands of individual sources including power plants, industrial operations, and heating boilers. Information for each plant includes location (latitude and longitude), fuel or product type, fuel consumption/material production, fuel quality (sulfur content and ash content), boiler type(s), boiler size, stack parameters, emission control technology for SO_2, NO_X, and PM, and their removal efficiencies. In the bottom-up approach, emissions for individual sources are aggregated to obtain the total emissions of the city. Emissions of SO_2 and PM were estimated using a mass-balance approach expressed by eqs 1 and 2, respectively.

$$E_{SO_2} = \sum_{i,j,k,m} A_{i,j,k,m} \times Scont_{i,m} \times (1 - Sr_{i,j,k,m}) \times (1 - \eta_n) \tag{1}$$

$$E_{PM,y} = \sum_{i,j,k,m} \sum_{n} A_{i,j,k,m} \times AC_{i,m} \times (1 - ar_{i,j,k,m}) \times f_{k,y} \times X_{k,n} \times (1 - \eta_{n,y}) \tag{2}$$

NO_X and NMVOC emissions were calculated using an emission factor methodology expressed by eq 3

$$E_p = \sum_{i,j,k,m} \sum_{n} A_{i,j,k,m} \times X_{j,k,m} \times EF_{j,k,m} \tag{3}$$

where i represents the i^{th} plant; j represents economic sector; k represents fuel or product type; m represents combustion and process technology type; n represents emission control technology; y represents particle size; A represents activity rate, such as fuel consumption or material production; $Scont$ is sulfur content of the fuel; Sr is percent of sulfur retained in the ash; AC is ash content of the fuel; ar is percent of ash as bottom ash; f is particulate mass fraction by size; X is the fraction of fuel or production for a sector that is consumed by a specific technology; EF is the emission factor; and η_n is the removal efficiency of control technology n.

A bottom-up methodology was applied to develop grid-based emissions from mobile sources in Beijing based on microscale vehicle activities and speed-dependent emission factors, which are described in a separate paper (*18*). The top-down approach was used for other area sources including household energy use, fugitive dust, and fugitive NMVOC emissions for which district-level statistical data were used (see Table 1). The emission factors are based on field measurement results from the Beijing Municipal Environment Monitoring Center (BMEMC) (*19*) and Tsinghua University (*20–25*) as shown in Tables 2 and 3.

Temporary Air Pollution Control Measures during the Olympic Games. Several temporary measures were employed to reduce emissions from mobile sources. About 347,000 vehicles that failed to meet the European No. I (Euro I) standards for vehicle exhaust emissions, termed “yellow label vehicles”, were banned from Beijing’s roads from July 1 to September 20, 2008. Seventy percent of government vehicles were ordered off the road during the Olympic Games. Private cars were allowed to travel on Beijing’s roads on alternate days depending on their license plate numbers (vehicles with a license plate ending in an odd number were allowed only on odd-number days while even numbers were allowed only on even-number days). Trucks were not allowed to run inside the sixth Ring Road between 6 a.m. to 12 a.m. without special passes.

TABLE 1. Activity Data To Estimate Emissions in June, 2008

	sector	activity	ref
coal combustion	power plants (kt)	763	*28*
	industrial boilers (kt)	319	*28*
	industrial stoves (kt)	281	*28*
	coking (kt)	100	*1*
	domestic use (kt)	117	*1*
natural gas combustion	power plants (10^9 m^3)	1.6	*28*
	industrial use (10^9 m^3)	2.7	*28*
	domestic use (10^9 m^3)	0.9	*28*
industrial processs	crude steel (kt)	330	*28*
	cement (kt)	1000	*28*
	coke (kt)	130	*28*
	gasoline (kt)	130	*28*
	diesel (kt)	150	*28*
transportation	mobile (1000 vehicles)	3250	*18*
	VKT (10^6 km/day)	126.6	*18*

Control measures were not limited to mobile source emissions. Other area and point sources in Beijing were also under strict control during and leading up to the Olympic Games. Power plants in Beijing were required to reduce their emissions by 30% from their June emission levels even though they already met the Emission Standard of Air Pollutants for Boilers in Beijing (DB11/139-2007). Approximately 50% of the coal-fired boilers temporarily ceased operation during the Olympic Games. Several heavy-polluting factories, including Capital Iron and Steel General Corporation and Beijing Yanshan Petro-Chemical Corporation, were required to reduce their operations by 30% to 50%. Most construction material manufacturers were shut down during the period. All construction activities were temporarily ceased. About 600 gas stations, oil depots, and fuel tankers were renovated with vapor recovery systems to minimize gasoline evaporation. Painting activities in the furniture-making and car-making industries were restricted. For different sources, the number percentage of plants which were closed or production reduced is given in Table S1 of the Supporting Information. Emission controls were also installed on large industrial sources located in surrounding provinces and Tianjin city.

Emission Reduction Monitoring. Continuous emission measurements (CEMs) data as well as Tsinghua University’s periodic in situ emission monitoring data from power plants and other industries were used to verify the effectiveness of control measures. The measurements indicated that TSP, SO_2, and NO_X emissions from power plants in June 2008 were 30% to 50% lower than that in June 2007. Emissions during the Olympic Games were further decreased by 30%. About 50% of the industrial boilers were closed, and all operating boilers met with the Emission Standard of Air Pollutants for Boilers in Beijing (DB11/139-2007).

Continuous traffic monitoring in urban Beijing illustrated the variation in transportation activity before and during the Olympic Games (*18*). Total urban vehicle kilometers traveled (VKT) was reduced by 32.0% during the Olympic Games. The average vehicle speed weighted by grid VKT increased from 25 km h^{-1} to 37 km h^{-1} during the Olympic Games. The emission factors for mobile sources also changed significantly

TABLE 2. Emission Factors for Stationary Sources (*19–25*)

	sector	SO_2	NO_X	PM_{10}	NMVOC
power plants[d]	Huaneng power plant[a,d]	0.243	1.296	0.081	1.170
	Jingneng power plant[a,d]	0.200	0.495	0.046	0.810
	Gaojing power plant[a,d]	0.255	0.592	0.098	0.810
	Guohua power plant[a,d]	0.076	0.810	0.085	1.170
	gas-fired power plants [b]	0.18	1.68	0.14	
industrial boilers[d]	coal-fired boilers above 20 t/h[a]	1.35	2.70	0.45	3.11
	coal fired boilers less than 20 t/h[a]	1.35	2.70	0.45	5.10
	gas fired boilers[b]	0.18	1.28	0.14	
domestic[a]		1.47	0.50	0.31	1.51
industrial processes[c]	cement production	0.31	1.01	2.09	
	lime production	3.72	1.27	2.27	
	oil refining				10.40
	coking		0.33		2.27
	pig iron		0.09		0.16
	sintering		0.04		
	refractory production	3.72	1.27	2.27	
	ferroalloy metallurgy			1.30	
	casting			0.14	

[a] Units in kg/t coal. [b] Units in g/m^3. [c] Units in kg/t products. [d] Data from Beijing Municipal Environmental Protection Bureau.

TABLE 3. Emission Factors for Mobile Sources (g/km)

	fuel	NO_X	PM_{10}	NMVOC
light duty vehicle	gasoline	0.827	0.011	1.647
light duty truck	gasoline	0.796	0.016	1.647
medium duty truck	gasoline	1.280	0.043	2.803
heavy duty truck	gasoline	1.997	0.151	3.446
light duty vehicle	diesel	0.758	0.239	0.379
medium duty truck	diesel	0.833	0.239	0.510
heavy duty truck	diesel	7.871	0.830	1.753
motorcycle	gasoline	0.031	0.012	2.324

due to (a) the change of vehicle speeds which were affected by traffic flow control and (b) fleet technology configurations which were influenced by prohibitions on yellow-label vehicles and strict operating restrictions on trucks. Real-world vehicle emission measurements were conducted using a Portable on-board Emissions Measurement System (PEMS) on a fixed route in Beijing both before and during the Olympic Games. The measurements show that CO, HC, and NO_X emission factors were reduced on average by 27%, 29%, and 1%, respectively, during the Olympic Games. At the same time, trip average speed increased from 26.8 km h^{-1} to 34.6 km h^{-1}.

Fugitive dust emissions from active construction sites also declined significantly. Monitoring of dust deposition near the boundaries of 20 construction sites by the Beijing Academy of Environmental Science showed an 80% to 90% reduction during the Olympic Games. Therefore, we hypothesized fugitive dust emissions from construction sites were reduced by more than 80% during the Olympic Games due to the restrictions on earth moving and concrete work.

Regional Air Quality Modeling System. Three-domain, one-way nesting was used in the MM5-Models-3/CMAQ modeling (see Figure S1, Supporting Information). The Lambert projection with the two true latitudes of 25°N and 40°N was used. The domain origin was 34°N, 110°E; the coordinates of the bottom left corner of the largest domain were $x = -2934$ km and $y = -1728$ km. Domain 1 with 36 × 36 km resolution covers most of East Asia. Domain 2 includes Beijing, Tianjin, Hebei, and parts of several surrounding provinces. The innermost domain, with 4 km grid spacing, consists of the whole Beijing and part of Tianjin and Hebei province. Fourteen vertical layers from the surface to the tropopause were employed. The corresponding sigma levels were 1.000, 0.995, 0.990, 0.980, 0.960, 0.940, 0.910, 0.860, 0.800, 0.740, 0.650, 0.550, 0.400, 0.200, and 0.000. The modeling period was from June 1 to August 31, 2008.

A combination of several emission inventories was used as the input of the CMAQ modeling system. Beijing's anthropogenic emissions were based on the detailed work as described above. For the whole China, a bottom-up approach was possible for large point sources as described by our previous paper (*20*), and for smaller and area sources a general top-down approach using provincial activity data for sources including small industry, mobile, domestic, and agriculture sources was used as described by Wei et al. (*26*) and Zhang et al. (*27*). Natural NMVOC emissions were calculated by MEGAN (*28*). It should be noted that fugitive dust emissions, such as road dust, construction dust, and wind-blown emissions from unpaved ground, were not available for the areas outside Beijing. CMAQ was run with and without emission reductions to analyze the impacts of control measures on air quality.

The fifth-generation NCAR/Penn State Mesoscale Model (MM5, version 3.7) was used to generate the meteorological fields. The National Center for Environmental Prediction (NCEP)'s Final Operational Global Analysis data were used to generate the first guess field with a horizontal resolution of 1° × 1°at every 6 h. The NCEP's Automated Data Processing (ADP) data was used in the objective analysis scheme. One-way nesting was applied in this simulation. The physics options selected in the MM5 model were Kain-Fritsch cumulus schemes (*29*), Pleim-Xiu PBL scheme (*30*), mixed phase explicit moisture schemes (*31*), cloud atmospheric radiation scheme (*32*), and the force/restore (Blackadar) surface scheme (*33, 34*).

This study applied CMAQ version 4.7. CMAQ was configured using the AERO5 aerosol module and the CB-05 chemical mechanism. Piecewise parabolic method (PPM) (*35*) and eddy diffusivity (K-theory) technique were chosen for advection and vertical diffusion, respectively. These options were typically used by CMAQ communities and were evaluated in Beijing for regional air quality simulations (*15–17*). The MCIP (Version 3.4.1) was applied to process the MM5 meteorological data for use with CMAQ. The initial conditions (ICON) for each period were prepared by running the model for five days before the first simulation day. It has been shown by sensitivity tests that the influence of initial conditions generally dissipates after 3 days (*36*). The boundary condition (BCON) used for Domain 1 was kept constant as

TABLE 4. Summary of Pollutants Emissions in Beijing (t/d)

	period							
	June 2008				Olympic period			
	SO$_2$[a]	NO$_X$[a]	PM$_{10}$[a]	NMVOC[a]	SO$_2$[a]	NO$_X$[a]	PM$_{10}$[a]	NMVOC[a]
power plants	11.4	34.3	1.8	24.2	8.2	16.3	1.8	24.7
building materials	24.1	42.4	35.4	9.6	3.6	6.9	2.9	2.8
chemical processing	9.5	5.2	3.0	4.6	5.0	3.7	2.1	2.6
metallurgy	16.8	3.4	11.0	5.7	12.5	22.4	8.9	4.1
industrial boilers	16.5	47.8	6.6	47.5	6.7	13.4	2.2	23.0
domestic stoves	25.6	13.4	5.5	5.9	25.6	13.4	5.5	5.9
mobile sources		282.0	15.9	371.3		153.0	7.7	165.0
fugitive emissions			283.6	421.3			121.5	153.7
total emissions	103.9	428.5	362.7	890.0	61.6	229.1	152.6	381.8

[a] Pollutants.

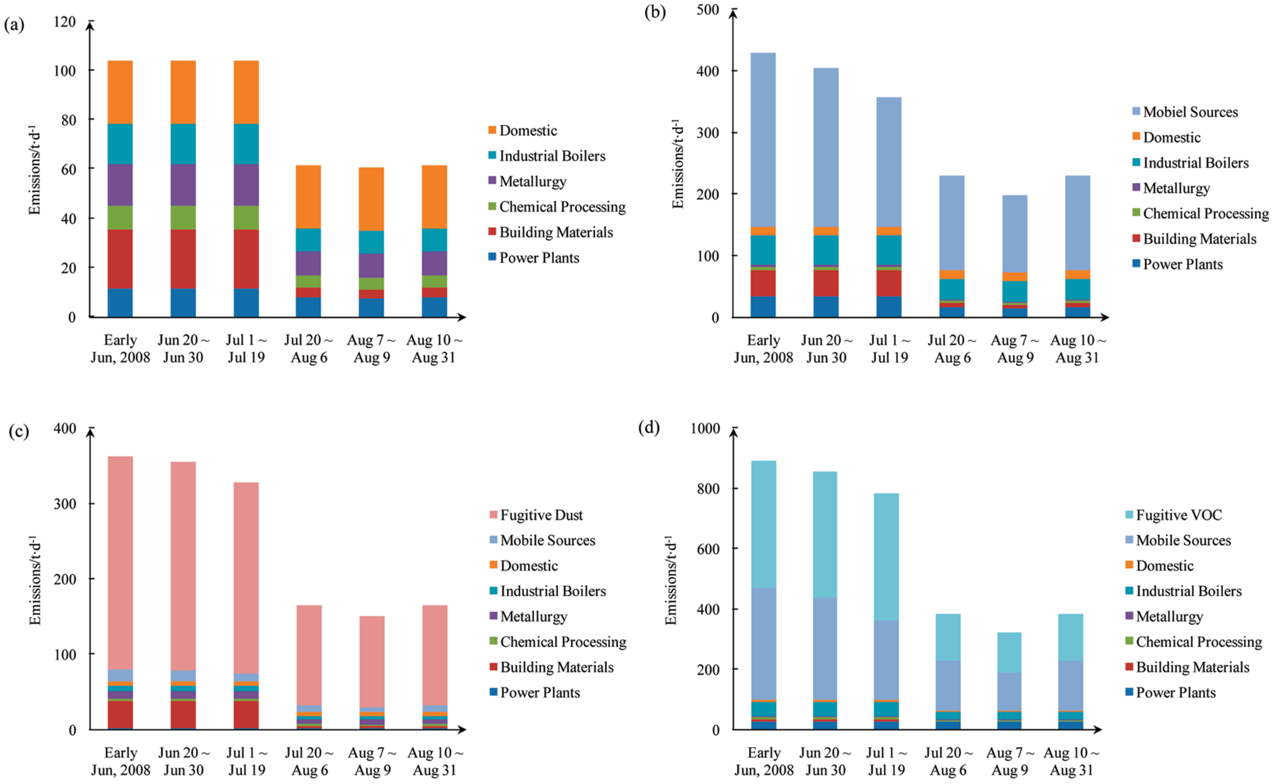

FIGURE 1. Emission reductions of air pollutants during the Olympic Games (a) SO$_2$; (b) NO$_X$; (c) PM$_{10}$; and (d) NMVOC.

the model default profile. The boundary conditions for the inner two domains were extracted from the outer domains.

Results and Discussion

Emissions before the Olympic Games. SO$_2$, NO$_X$, PM$_{10}$, and NMVOC emissions in June, 2008 are shown in Table 4. In June 2008, the daily emissions of SO$_2$, NO$_X$, PM$_{10}$, and NMVOC were 103.9 t, 428.5 t, 362.7 t, and 890.0 t, respectively. Fugitive dust was the largest PM$_{10}$ emission source, which contributed 79% of total PM$_{10}$ emissions in Beijing. Domestic coal combustion, building material manufacturing, metallurgy, industrial boilers, and power plants were the largest contributors to SO$_2$ emissions, which respectively accounted for 25%, 23%, 16%, 16%, and 11% of total SO$_2$ emissions in Beijing. Fugitive NMVOCs sources and mobile sources were the largest sources for NMVOC emissions. Mobile sources, industrial boilers, and building material manufacturing were the largest NO$_X$ emission sources, accounting for 66%, 11%, and 10% of total NO$_X$ emissions in Beijing, respectively.

Emission Reduction during the Olympic Games. The daily emissions of SO$_2$, NOx, PM$_{10}$, and NMVOC during Olympics are given in Table 4. During the Olympic Games, as a result of the temporary air pollution control measures, daily emissions of SO$_2$, NO$_X$, PM$_{10}$, and NMVOC were reduced by 41%, 47%, 55%, and 57%, respectively, compared to emissions in June 2008.

Figure 1(a) shows the SO$_2$ emission reductions attributable to temporary air pollution control measures. SO$_2$ emissions declined from 103.9t/d in June 2008 to 61.6t/d during the Olympic Games. SO$_2$ emissions from building material manufacturing decreased 85% due to the temporary closure of most sources. This reduction represents 48% of the total SO$_2$ emission reductions during the Olympic Games.

Figure 1(b) shows the NO$_X$ emission reductions attributable to temporary air pollution control measures. NO$_X$ emissions were 428.5t/d in June 2008 and between 197 and 229t/d during the Olympic Games. NO$_X$ emission reductions from vehicles played an important role during the Olympic Games. Prohibitions of yellow-label vehicles reduced total NO$_X$ emissions by 17% from June 2008 levels. In late July, the odd−even traffic restrictions as well as the emission limits on power plants and industrial sources reduced total NO$_X$

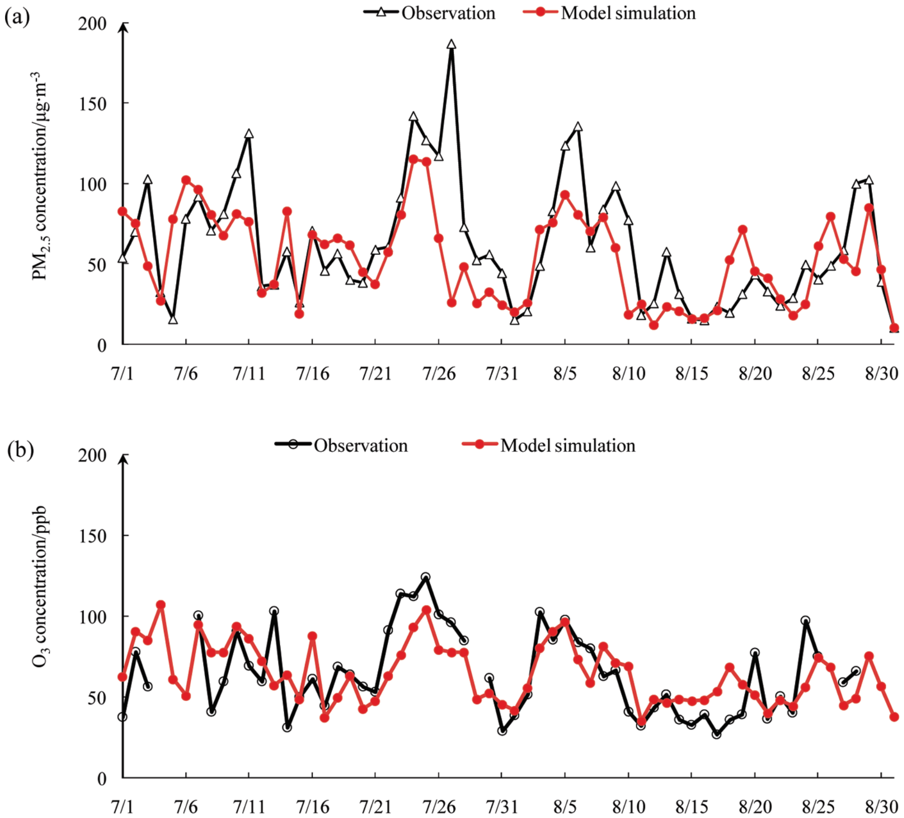

FIGURE 2. Comparison of day-to-day variations of monitored $PM_{2.5}$ (Tsinghua station) and afternoon mean O_3 (Miyun station) and CMAQ model results (a) $PM_{2.5}$ and (b) O_3.

emissions to 229.1t/d. NO_X emissions decreased by another 32.0t on August 8, 2008, the start of the Olympic Games, because of lower traffic flow on that day. NO_X emissions from mobile sources decreased 46% because of restrictions on vehicle operation. This contributed 65% of the NO_X reductions during the Olympic Games.

Figure 1(c) shows the PM_{10} emission reductions during the Olympic Games. PM_{10} emissions in June 2008 were 362.7t/d and 152.6t/d during the Olympic Games, a 55% decrease. Temporary measures to stop work at construction sites and shut down industrial kilns during the Olympic Games yielded significant emission reductions. Fugitive dust emission control measures at construction sites and industrial sources contributed 35% and 34% to PM_{10} emission reductions, respectively.

NMVOC emission reductions are shown in Figure 1(d). NMVOC emissions were 890.0t/d before the Olympic Games and 381.8t/d during the Olympic Games, a 57% reduction. Over 93% of the NMVOC reductions came from the restriction of the vehicles and the emissions control of fugitive sources. Daily NMVOC emissions from mobile sources were reduced from 371.3t in June 2008 to 165.0t during the Olympic Games, a decrease of 57%. This contributed 42% of the NMVOC reductions. Daily fugitive NMVOC emissions were reduced from 421.3t in June 2008 to 153.7t during the Olympic Games. A decrease of fugitive NMVOC emissions was mainly due to the production suspension/reduction of various industrial plants, as shown in Table S1.

Validating Air Quality Simulation Results. The emission inventory and CMAQ model were evaluated by comparing predicted simulation results with observation data. Daily PM_{10} concentrations were compared with Air Pollution Index (API) data measured by Beijing Environmental Monitoring Center (http://www.bjee.org.cn/cn/index.php). Simulated daily PM_{10} concentrations were 107 $\mu g/m^3$ in June, 88 $\mu g/m^3$ in July, and 81 $\mu g/m^3$ in August. In comparison, the observed concentrations were 130 $\mu g/m^3$ in June, 90 $\mu g/m^3$ in July, and 71 $\mu g/m^3$ in August. The mean bias deviation (MBE) between observations and CMAQ simulations were −18% in June, −17% in July, and 13% in August. Based on API data, the changes of average PM_{10}, SO_2, and NO_2 concentrations from June 1 to August 31 were also calculated to indicate the impacts of emission reduction on air quality (Figure S2). Figure S2 indicated that the average PM_{10}, SO_2, and NO_2 concentrations during the Olympics period were 46%, 35%, and 62% lower than those in June 2008, which generally agreed with our estimates on emission reductions. Our simulation results were also consistent with the satellite observations. Based on Ozone Monitoring Instrument (OMI) data, it was reported that NO_2 concentrations were reduced approximately 60% above Beijing during the 2008 Olympic Games (*37*). Our model gave very similar results. The OMI data we used were for the Beijing area (115.5−117E, 39.5−41N), with a spatial resolution of 0.125 × 0.125 degree. Grid to grid comparison between the model results and OMI NO_2 retrieves (OMI) indicates that the Pearson correlation coefficient is 0.85, with a normalized mean bias (NMB) of −9% (Figure S3).

For $PM_{2.5}$, there are only measurements at a monitoring site located at Tsinghua University available for limited time periods (July 1−August 31, 2008). Therefore we compared the modeled daily $PM_{2.5}$ concentrations with the $PM_{2.5}$ observations from this site, as shown in Figure 2(a). In general, the model simulation was able to capture the trends of daily variations of $PM_{2.5}$. The Pearson correlation coefficient between modeled and observed data was 0.6 for the whole period and 0.7 for August. CMAQ tended to overestimate in some cases, for example, July 1 and August 18−19. However, the model tended to underestimate for high $PM_{2.5}$ events, such as July 24−28 and August 28−29. This might be partly due to an under- or overestimation of wind speed. For ozone, we were able to compare the predicted afternoon mean O_3 concentrations (12:00−18:00) with observations at a monitoring site located at Miyun, about 100 km northeast of the

Beijing urban center (*38*), as shown in Figure 2(b). In general, the agreement between modeled and observed O_3 concentrations was good, and the model simulation was able to capture the daily variations of O_3. Exceptions were the underestimation of O_3 concentrations for July 22−26 and the overestimation of O_3 concentrations for August 14−19, 2008.

Since all emission reduction measures had been put in place before August 1, 2008, emissions were expected to stay relatively constant throughout August except on the opening day of the Olympic Games (August 8), which was declared a public holiday for Beijing. Therefore, the day to day variability in $PM_{2.5}$ and O_3 concentrations presumably reflects changes due to variations in meteorological conditions and chemical lifetimes of relevant chemical species. We ran another CMAQ case using June's emission inventory (without emission reduction) and analyzed the impacts of implementing the Olympic emission reductions. According to the model results, the mean meteorology-driven anomaly was $-11\ \mu g/m^3$ and the mean emission-driven anomaly was $-27\ \mu g/m^3$. This implied that both emission reduction and meteorology helped Beijing improve air quality. However, more than 60% of $PM_{2.5}$ concentration decreases were attributed to the emission reduction during the Olympic Games.

For ozone, Wang et al. (*38*) suggested that the mean daytime mixing ratio of O_3 was reduced by about 15 ppbv in during the Olympic Games compared to that in August 2006−2007. Wang et al. (*38*) also concluded that emission restrictions during the Olympic Games were responsible for about 80% of the observed O_3 decreases in Miyun. Ozone concentration changes were quite affected by the reduction of VOC and NO_X emissions. During the Olympic Games, daily VOC emissions decreased 507t and NO_X emissions decreased 202t. Correspondingly, the VOC/NO_X emission ratio in Beijing decreased from 2.07 in June to 1.69 in August. Because of the temporary control measures, the VOC/NO_X emission ratio in surrounding provinces decreased from 1.99 in June to 1.95 in August. According to the CMAQ model, daily maximum O_3 concentrations in August 2008 were more sensitive to VOC control. However, reductions of both NO_x and VOC emissions would decrease the daily maximum O_3 concentrations (Figure S4). This explained the effectiveness of emission control measures during the Olympic Games.

Because China is presently undergoing rapid economic growth, there are threats of serious fine particles and ozone pollution in many large cities in China. The experience of air pollution control during the Beijing Olympic Games can help in air pollution control in other cities. One important implication is that better air quality can be achieved if strict integrated measures are implemented to control multipollutant emissions (SO_2, NO_X, PM, VOC, etc.). Second, controlling fugitive dusts from construction sites, roads, and industries are key measures to reduce PM emissions. Improvement of the traffic system including travel demand management can effectively reduce emissions from mobile sources. In addition, studies shall be conducted to determine the appropriate control ratio of NO_X and VOC to effectively alleviate photochemical pollution.

Acknowledgments

We thank Mr. Jeremy Schreifels of the U.S. EPA for his great help in revising this paper. This study was funded by MEP's Special Funds for Research on Public Welfares (No. 200709032), Beijing Municipal Environment Protection Bureau and National Science Foundation of China (No. 20437010). The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the sponsors.

Supporting Information Available

Table S1 and Figures S1−S4. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Beijing Municipal Bureau of Statistics. *Beijing Statistical Yearbook 2008*; China Statistics Press: Beijing, 2009.

(2) Hao, J.; Wang, L.; Li, L.; Hu, J.; Yu, X. Air pollutants contribution and control strategies of energy-use related sources in Beijing. *Sci. China, Ser. D: Earth Sci.* **2005**, *48* (Suppl. II), 138–146.

(3) Beijing Environmental Bulletin 2000−2007. Available at http://www.bjepb.gov.cn (accessed March 10, 2010).

(4) He, K.; Yang, F.; Ma, Y.; Zhang, Q.; Yao, X.; Chan, C. K.; Cadle, S. H.; Chan, T.; Mulawa, P. A. The characteristics of $PM_{2.5}$ in Beijing, China. *Atmos. Environ.* **2001**, *35*, 4959–4970.

(5) Hao, J.; Wang, L. Improving urban air quality in China: Beijing case study. *J. Air Waste Manage. Assoc.* **2005**, *55*, 1298–1305.

(6) Chan, C.; Xu, X.; Li, Y.; Wong, K.; Ding, G.; Chan, L.; Cheng, X. Characteristics of vertical profiles and sources of $PM_{2.5}$, PM_{10} and carbonaceous aerosols in Beijing. *Atmos. Environ.* **2005**, *39*, 5113–5124.

(7) Zheng, M.; Salmon, L. G.; Schauer, J. J.; Zeng, L.; Kiang, C. S.; Zhang, Y.; Cass, G. R. Seasonal trends in $PM_{2.5}$ source contributions in Beijing, China. *Atmos. Environ.* **2005**, *39*, 3967–3976.

(8) Wang, Y.; Zhuang, G.; Tang, A.; Yuan, H.; Sun, Y.; Chen, S.; Zheng, A. The ion chemistry and the source of $PM_{2.5}$ aerosol in Beijing. *Atmos. Environ.* **2005**, *39*, 3771–3784.

(9) Wang, T.; Ding, A.; Gao, J.; Wu, W. S. Strong ozone production in urban plumes from Beijing, China. *Geophys. Res. Lett.* **2006**, *33*, L21806. doi:10.1029/2006GL027689.

(10) Wang, Y.; McElroy, M. B.; Munger, J. W.; Hao, J.; Ma, H.; Nielsen, C. P.; Chen, Y. Variations of O_3 and CO in summertime at a rural site near Beijing. *Atmos. Chem. Phys.* **2008**, *8*, 6355–6363.

(11) Huo, H.; Zhang, Q.; He, K.; Wang, Q.; Yao, Z.; Streets, D. G. High-Resolution Vehicular Emission Inventory Using a Link-Based Method: A Case Study of Light-Duty Vehicles in Beijing. *Environ. Sci. Technol.* **2009**, *43*, 2394–2399.

(12) Wang, H.; Fu, L.; Lin, X.; Zhou, Y.; Chen, J. A bottom-up methodology to estimate vehicle emissions for the Beijing urban area. *Sci. Total Environ.* **2009**, *407*, 1947–1953.

(13) Wang, Y.; McElroy, M. B.; Boersma, K. F.; Eskes, H. J.; Veefkind, J. P. Traffic Restrictions Associated with the Sino-African Summit: Reductions of NOx Detected from Space. *Geophys. Res. Lett.* **2007**, *34*, L08814. doi:10.1029/2007GL029326.

(14) Cheng, Y. F.; Heintzenberg, J.; Wehner, B.; Wu, Z. J.; Hu, M.; Mao, J. T. Traffic restrictions in Beijing during the Sino-African Summit 2006: aerosol size distribution and visibility compared to long-term in situ observations. *Atmos. Chem. Phys.* **2008**, *8*, 7583–7594.

(15) Streets, D. G.; Fu, J. S.; Jang, C. J.; Hao, J.; He, K.; Tang, X.; Zhang, Y.; Wang, Z.; Li, Z.; Zhang, Q.; Wang, L.; Wang, B.; Yu, C. Air quality during the 2008 Beijing Olympic Games. *Atmos. Environ.* **2007**, *41*, 480–492.

(16) Wang, L.; Hao, J.; He, K.; Wang, S.; Li, J.; Zhang, Q.; Streets, D. G.; Fu, J. S.; Jang, C. J.; Takekawa, H.; Chatani, S. A modeling study of coarse particulate matter pollution in Beijing: Regional source contributions and control implications for the 2008 summer Olympics. *J. Air Waste Manage. Assoc.* **2008**, *58* (8), 1057–1069.

(17) Wang, S.; Chen, Y.; Xu, J.; Hao, J. Study on Air Quality Impacts and Control Strategies of Coal Combustion in Beijing. *Chin. J. Environ. Eng.* **2010**, *4* (1), 151–158.

(18) Zhou, Y.; Wu, Y.; Yang, L.; Fu, L.; He, K.; Wang, S.; Hao, J.; Chen, J.; Li, C. The impact of transportation control measures on emission reductions during the 2008 Olympic Games in Beijing, China. *Atmos. Environ.* **2010**, *44* (3), 285–293.

(19) Beijing Environmental Monitoring Center (BEMC). *Study on the air pollution status and emission sources in Beijing*; BEMC: Beijing, 2006 (in Chinese).

(20) Zhao, Y.; Wang, S.; Duan, L.; Lei, Y.; Cao, P.; Hao, J. Primary air pollutant emissions of coal-fired power plants in China: Current status and future prediction. *Atmos. Environ.* **2008**, *42* (36), 8442–8452.

(21) Yi, H.; Hao, J.; Duan, L.; Li, X.; Guo, X. Characteristics of inhalable particulate matter concentration and size distribution from power plants in China. *J. Air Waste Manage. Assoc.* **2006**, *56*, 1243–1251.

(22) Li, X.; Wang, S.; Duan, L.; Hao, J.; Li, C.; Chen, Y.; Yang, L. Particulate and Trace Gas Emissions from Open Burning of Wheat Straw and Corn Stover in China. *Environ. Sci. Technol.* **2007**, *41*, 6052–6058.

(23) Yi, H.; Hao, J.; Duan, L.; Tang, X.; Ning, P.; Li, X. Fine particle and trace element emissions from an anthracite coal-fired power plant equipped with a bag-house in China. *Fuel* **2008**, *87* (10−11), 2050–2057.

(24) Li, X.; Duan, L.; Wang, S.; Duan, J.; Guo, X.; Yi, H.; Hu, J.; Li, C.; Hao, J. Emission Characteristics of Particulate Matter from Rural Household Biofuel Combustion in China. *Energy Fuels* **2007**, *21*, 845–851.

(25) Wang, S.; Zhao, X.; Li, X.; Wei, W.; Hao, J. Emission characteristics of fine particles from grate firing boilers. *Environ. Sci.* **2009**, *30* (4), 963–968 (in Chinese).

(26) Wei, W.; Wang, S.; Chatani, S.; Klimont, Z.; Cofala, J.; Hao, J. Emission and speciation of non-methane volatile organic compounds from anthropogenic sources in China. *Atmos. Environ.* **2008**, *42*, 4976–4988.

(27) Zhang, Q.; Streets, D. G.; Carmichael, G. R.; He, K.; Huo, H.; Kannari, A.; Klimont, Z.; Park, I.; Reddy, A.; Fu, J.; Chen, D.; Duan, L.; Lei, Y.; Wang, L.; Yao, Z. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos. Chem. Phys. Discuss.* **2009**, 4081–4139.

(28) Müller, J. F.; Stavrakou, T.; Wallens, S.; De Smedt, I.; Van Roozendael, M.; Potosnak, M. J.; Rinne, J.; Munger, B.; Goldstein, A.; Guenther, A. B. Global isoprene emissions estimated using MEGAN, ECMWF analyses and a detailed canopy environment model. *Atmos. Chem. Phys.* **2008**, *8*, 1329–1341.

(29) Kain, J. S.; Fritsch, J. M. Convective parameterization for mesoscale models: The Kain-Fritsch scheme. In *The representation of cumulus convection in numerical models of the atmosphere*; Emanuel, K. A., Raymond, D. J., Eds.; Amer. Meteor. Soc.: Geneseo, NY, 1993.

(30) Zhang, D. L.; Anthes, R. A. A high-resolution model of the planetary boundary layer - sensitive tests and comparisons with SESAME-79 data. *J. Appl. Meteor.* **1982**, *21*, 1594–1609.

(31) Reisner, J.; Rasmussen, R. J.; Bruintjes, R. T. Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Q. J. R. Meteorol. Soc.* **1998**, *124B*, 1071–1107.

(32) Dudhia, J. A non-hydrostatic version of the Penn State/NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front. *Mon. Weather Rev.* **1993**, *121*, 1493–1513.

(33) Blackadar, A. K. Modeling the Nocturnal Boundary Layer. Proc. In *Third Symposium on Atmospheric Turbulence, Diffusion and Air Quality*; Amer. Meteor. Soc.: Boston, 1976.

(34) Deardorff, J. W. Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *J. Geophys. Res.* **1978**, *83*, 1889–1903.

(35) Colella, P.; Woodward, P. R. The piecewise parabolic method (PPM) for gas dynamical simulations. *J. Comp. Phys.* **1984**, *54*, 174–201.

(36) Jang, C. J.; Dolwick, P.; Possiel, N.; Timin, B.; Braverman, T.; Tikvart, J. Evaluation and sensitivity studies of US EPA's Models-3/CMAQ annual simulations over the continental United States. In *95th Annual A&WMA's Conference and Exhibition*; Baltimore, MD, 2002.

(37) Mijling, B.; van der A, R. J.; Boersma, K. F.; Van Roozendael, M.; De Smedt, I.; Kelder, H. M. Reductions of NO_2 detected from space during the 2008 Beijing Olympic Games. *Geophys. Res. Lett.* **2009**, *36 13*, L13801–13806.

(38) Wang, Y.; Hao, J.; McElroy, M. B.; Munger, J. W.; Ma, H.; Chen, D.; Nielsen, C. P. Ozone air quality during the 2008 Beijing Olympics: effectiveness of emission restrictions. *Atmos. Chem. Phys.* **2009**, *9*, 5237–5251 .

ES9028167