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Air quality during the 2008 Beijing Olympic Games

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Abstract

China is taking major steps to improve Beijing's air quality for the 2008 Olympic Games. However, concentrations of fine particulate matter and ozone in Beijing often exceed healthful levels in the summertime. Based on the US EPA's Models-3/CMAQ model simulation over the Beijing region, we estimate that about 34% of $PM_{2.5}$ on average and 35–60% of ozone during high ozone episodes at the Olympic Stadium site can be attributed to sources outside Beijing. Neighboring Hebei and Shandong Provinces and the Tianjin Municipality all exert significant influence on Beijing's air quality. During sustained wind flow from the south, Hebei Province can contribute 50–70% of Beijing's $PM_{2.5}$ concentrations and 20–30% of ozone. Controlling only local sources in Beijing will not be sufficient to attain the air quality goal set for the Beijing Olympics. There is an urgent need for regional air quality management studies and new emission control strategies to ensure that the air quality goals for 2008 are met.

Keywords: Beijing; Regional air quality; Olympic Games; $PM_{2.5}$; Ozone

1. Introduction

Beijing will host the 2008 Summer Games of the XXIX Olympiad from August 8–24, 2008. This is an event of paramount importance to China, and great steps are being taken to ensure its complete success. Of concern both within and outside China is the air quality that athletes and attendees will face during the Games. China wishes to ensure a healthful and enjoyable experience for all. However, air pollution levels in the summertime in Beijing can be high. Significant improvements in air quality in China were achieved during the late 1990s and early 2000s (Hao and Wang, 2005), but with reinvigorated economic growth and continued expansion of the transportation system, some of those gains have been lost in the last few years.

The Beijing and National governments are introducing many new pollution control measures designed to reduce local emissions in Beijing, as

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specified by the Beijing Organizing Committee of the XXIX Olympic Games (BOCOG) (2004). Undoubtedly, by August 2008, local sources of air pollution will be considerably fewer than they are today. However, there is a concern that much of the air pollution experienced in Beijing is regional in nature and not attributable to local sources. Thus, control measures implemented only in Beijing may not reduce ambient pollutant concentrations to acceptable levels. The purpose of this study is to examine the contribution of sources outside Beijing to air pollution levels in summertime Beijing. We consider two of the most important regional and urban air pollutants: fine particulate matter (PM) and ozone (O_3). We examine the contributions of neighboring provinces and suggest priorities for addressing regional air pollution concerns.

Fig. 1 shows the locations of the Beijing and Tianjin Municipalities that contain the cities of Beijing (population 11.5 million) and Tianjin (9.3 million) (National Bureau of Statistics of China (NBS), 2004). Surrounding them are three large provinces—Hebei, Shandong, and Shanxi—all heavily populated, urbanized, and industrialized. Also shown in Fig. 1 are the four large urban centers of Shijiazhuang (9.1 million), Qingdao (7.2 million), Jinan (5.8 million), and Taiyuan (3.3 million), which are typical industrial, coal-burning cities within several hundred kilometers of Beijing. In these areas, emission controls on stationary sources and vehicles are not as stringent as in Beijing, and emissions are high. Rural biomass burning has also been identified as an important contributor to fine PM concentrations in Beijing (Duan et al., 2004). Emissions from these nearby sources, as well as more distant ones, undergo chemical reactions during transport on the prevailing winds, forming secondary species that pervade the entire region and add to the local pollution in Beijing (Han et al., 2005; Hatakeyama et al., 2005; Luo et al., 2000; Mauzerall et al., 2000). Episodic dust storms in the springtime also contribute to the PM loading in Beijing (Dillner et al., 2006; Xie et al., 2005).

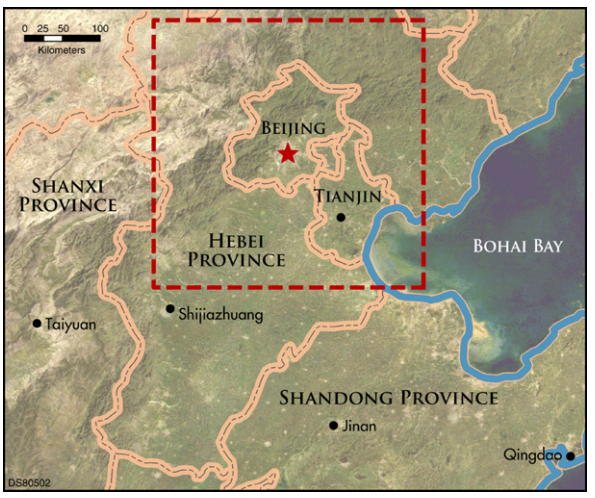

Fig. 1. Map of Beijing and the surrounding area, showing the 4-km modeling domain.

Fine PM, here considered as either $PM_{2.5}$ (particles with average diameters $\leqslant$2.5 micrometers [μm]) or PM_{10} (diameters $\leqslant$10 μm), is directly emitted from power plants, motor vehicles, industrial facilities, and other sources. It is also formed photo-chemically from reactions of primary gaseous species in the atmosphere, e.g., ammonium sulfate, ammonium nitrate, and secondary organic aerosols formed from reactions among sulfur dioxide, nitrogen oxides (NO_x), volatile organic compounds (VOC), and ammonia (Lun et al., 2003; Tang et al., 2005; Zhang et al., 2000). In summertime, the high temperatures and high humidity promote the photochemical formation of ozone (Xiao and Zhu, 2003), exacerbated by the heat island effect (Lin and Yu, 2005). Fine PM and ozone are considered to be the most serious air pollutants of concern in the US today, as well as in most metropolitan areas around the world. It is imperative to reduce the concentrations of these two pollutants during the Olympic Games.

2. Background

In 1997 the US Environmental Protection Agency (US EPA) revised the National Ambient Air Quality Standards (NAAQS) that have been established to protect public health and the environment. The revised PM standards include an annual average $PM_{2.5}$ standard of 15 $\mu g\,m^{-3}$ and a daily average $PM_{2.5}$ standard of 65 $\mu g\,m^{-3}$, in addition to an annual PM_{10} standard of 50 $\mu g\,m^{-3}$ and a daily average PM_{10} standard of 150 $\mu g\,m^{-3}$ (US Environmental Protection Agency (US EPA), 1997a). China also has ambient air quality standards for PM, codified in 1996, which it classifies according to three grades. China's daily average PM_{10} standards are 50 $\mu g\,m^{-3}$ (Grade I), 150 $\mu g\,m^{-3}$ (Grade II), and 250 $\mu g\,m^{-3}$ (Grade III) (China State Environmental Protection Administration (SEPA), 1996; Hao and Wang, 2005). China's annual PM_{10} standards are

40 μg m^{-3} (Grade I), 100 μg m^{-3} (Grade II), and 150 μg m^{-3} (Grade III). The Grade II standard is applied to urban areas like Beijing. Thus, Beijing's daily average PM_{10} standard is the same as for the US. There is no standard in China for $PM_{2.5}$ at present.

There have been many measurements of fine PM in Beijing made over the past five years (summarized in Table 1). These studies have found average summertime daily PM_{10} concentrations to range from 94 to 251 μg m^{-3} (Bergin et al., 2001; Chan et al., 2005). A maximum value of 368 μg m^{-3} was measured at the Southern Observational Base (SB) of the Chinese Academy of Meteorological Sciences (CAMS) in August 2003 (Chan et al., 2005). Thus, average concentrations of PM_{10} in Beijing have often exceeded the US NAAQS and China's Grade II standard in recent years. Occasionally, there have been exceedances of China's Grade III standard of 250 μg m^{-3} for daily PM_{10} concentrations. Daily $PM_{2.5}$ concentrations in Beijing have been found to be very high in comparison to the US NAAQS value of 65 μg m^{-3}. Average daily $PM_{2.5}$ concentrations in recent studies ranged from 91 to 169 μg m^{-3} (Bergin et al., 2001; Chan et al., 2005).

Many studies (Dan et al., 2004; He et al., 2001, 2004; Sun et al., 2004; Wang et al., 2005; Xu et al., 2005; Zheng et al., 2005) have measured weekly to seasonally averaged concentrations of fine PM, and the summertime measurements are particularly useful indicators of recent air quality. The averages of measured daily PM_{10} concentrations during summer range from 150 to 172 μg m^{-3} (Sun et al., 2004). For $PM_{2.5}$, the averages of measured daily concentrations range from 75 to 145 μg m^{-3} across the various studies. It can be concluded that in recent years both PM_{10} and $PM_{2.5}$ concentrations in the summer months have been consistently above healthful levels. The World Health Organization (WHO) has not issued a guideline for acceptable

Table 1
Summary of measurements of fine particle concentrations in Beijing (concentrations reported for periods of a week or longer are averaged from daily values; concentrations shown are average values with ranges given in parentheses)

Measurement intervals	PM_{10} concentration (μg m^{-3})	$PM_{2.5}$ concentration (μg m^{-3})	Monitoring site(s)	Time period of measurements	Reference
Hourly	(4.5–374)	89 (2.9–300)	IP (urban)	8/2003	Chan et al. (2005)
Daily	167 (52–272)	91 (30–159)	CM (urban)		
	251 (177–368)	114 (84–163)	SB (suburban)		
	94 (3.5–179)	169 (19–368)	IP, CM, SB (urban/suburban)		
	192	136	PU (suburban)	6/1999	Bergin et al. (2001)
	150	65	US National Ambient Air Quality Standards (US EPA, 1997a)		
	50, 150, 250		China Ambient Air Quality Standards (Grade I, Grade II, Grade III) (China SEPA, 1996)		
Weekly		(37–357)	TU, CG (urban)	7/1999–9/2000	He et al. (2001)
Monthly		99	DS, PU, AP, YL, MT (urb/sub)	7/2000	Zheng et al. (2005)
	112	33	BN (urban)	7/2002	Xu et al. (2005)
Seasonal (summer)		93	BN, CS, YH, MY, PG (urb/sub)	Summer 2001–2003	Wang et al. (2005)
		76	CG (urban)	Summer 2000	He et al. (2001)
		145	BJ (urban)	7/2002–8/2002	He et al. (2004)
		104	BN (urban)	7/2001–8/2001	Dan et al. (2004)
		122	PG (rural)		
		91	BN, CS, YH (urban)	6/2002–7/2002	
	172 (24–462)	77 (16–216)	BN (urban)	Summer 2002–2003	Sun et al. (2004)
	170 (51–311)	82 (12–170)	CS (urban)		
	150 (64–276)	75 (15–180)	YH (urban)		

IP = Institute of Atmospheric Physics, CM = Chinese Academy of Meteorological Sciences, SB = Southern Observational Base, PU = Peking University, TU = Tsinghua University, CG = Chegongzhuang, DS = DongSi Environmental Protection Bureau, AP = airport, YL = Yong Le Dian, MT = Ming Tombs, CS = Capital Steel Company, YH = Yihai Garden, PG = Pinggu, MY = Miyun, BJ = Beijing (unspecified), BN = Beijing Normal University.

Fig. 2. Illustrative example of Beijing's air quality contrasts: October 29, 2005, Air Pollution Index (API) = 48, PM_{10} concentration $\sim 50\,\mu g\,m^{-3}$ (left); October 26, 2005, API = 176, PM_{10} concentration $\sim 300\,\mu g\,m^{-3}$ (right).

fine PM concentrations, arguing that health effects research does not support setting a threshold below which concentrations are not harmful; that is to say, fine PM is considered harmful even at very low concentrations (WHO, 2006).

Fig. 2 depicts in dramatic fashion how poor Beijing's air quality can be and how quickly it can change. The right photograph shows air quality on October 26, 2005. This was during a period of air stagnation with low wind speeds and no precipitation that caused fine PM to accumulate. The local Air Pollution Index was 176 on this day, equivalent to a PM_{10} concentration of $\sim 300\,\mu g\,m^{-3}$. The left photograph shows the situation just three days later, on October 29, 2005, after a period of rain and wind. The API value decreased to 48 and the PM_{10} concentration was $\sim 50\,\mu g\,m^{-3}$.

Although there are fewer published measurements of ambient ozone concentrations in Beijing than of fine PM concentrations, ozone remains a critically important component of regional air pollution in Beijing. The US NAAQS ozone standard is set at 80 parts per billion (ppb) on an 8-h average (US Environmental Protection Agency (US EPA), 1997b), which replaced a prior 1-h standard of 120 ppb. China's ozone standard is set on an hourly-average basis and was revised in 2000 (Hao and Wang, 2005) to $0.16\,mg\,m^{-3}$ (Grade I), $0.20\,mg\,m^{-3}$ (Grade II), and $0.20\,mg\,m^{-3}$ (Grade III). These standards are approximately equivalent to 80, 100, and 100 ppb in the Beijing atmosphere. The WHO guideline (WHO, 2006) for ozone is 60 ppb as an 8-h average. One Beijing study that was reported in the literature measured an average daily ozone concentration in summer of $0.093\,mg\,m^{-3}$ with a peak value of $0.178\,mg\,m^{-3}$ (Sun et al., 2004). Hao and Wang (2005) reported that measurements by the Beijing Environmental Protection Bureau showed ozone concentrations in 1998 exceeding the standard on 101 days or 504 hours. The highest measured hourly concentration was $0.384\,mg\,m^{-3}$. Therefore, as for fine PM, exceedances of the US NAAQS and the China Grade II standard for ozone are common.

3. Methodology

In this present work, Beijing's air quality is simulated using the Models-3/Community Multiscale Air Quality (CMAQ) modeling system (Version 4.4), developed by the US EPA (Byun and Ching, 1999). The CMAQ model has received many applications and evaluations in the US and other countries for regional- and urban-scale air quality simulations, integrating a number of air quality issues (particulate matter, ozone, acid deposition, visibility, air toxics, etc.) into a so-called "one-atmosphere" approach. The driving meteorological inputs for this work are provided by the fifth-generation NCAR/Penn State Mesoscale Model (MM5), version 3.6.2. The pollution episode studied is from July 1–31, 2001, with a spin-up period of 5 days starting on June 26, 2001. Neither the required meteorological data nor any PM_{10} measurement data are available for the month of August, so we use July as a summertime proxy for the month of August when the Olympic Games will be held. The model was run in a nested grid mode at 36, 12, and

4 km resolutions. The 36-km grid domain consists of all of China, the Koreas, Japan, and parts of India and Southeast Asia; the 12-km domain consists of East China and the Koreas; and the innermost 4-km domain consists of Beijing and surrounding areas (shown in Fig. 1). The model employs 14 vertical layers of varying thickness with denser layers in the lower atmosphere to better resolve the mixing layer.

Emissions are taken from the NASA TRACE-P emission inventory (Streets et al., 2003), updated for the city of Beijing to take account of detailed local information on source strengths and locations. Table 2 summarizes the emissions used in the modeling for Beijing, Tianjin, and the three neighboring provinces. Note that these five provinces together contribute 16–32% (depending on species) of China's total national emissions.

Though the CMAQ model has received extensive evaluation in the US and other countries, it has not previously been applied in China. The atmosphere of eastern China poses a number of challenges, including the complex mesoscale meteorology caused by rapidly evolving land-use patterns and the possibly unique interactions between reactive gas-phase species like ozone and high loadings of aerosols. Model evaluation is made more difficult by the absence of routine monitoring data for species like ozone and fine PM. Historical measurements have focused on regulated pollutants like SO_2 and TSP, and recently PM_{10} and NO_x/NO_2 have been added in some areas. But there are only scattered measurements of $PM_{2.5}$ and ozone for limited time periods at one or two research sites.

The CMAQ model was initially evaluated by comparing predicted daily PM_{10} concentrations for July 2001 against Air Pollution Index (API) data measured by the Beijing Environmental Monitoring Center (Fig. 3). In addition, predicted $PM_{2.5}$ concentrations were compared against a set of weekly measurements of $PM_{2.5}$ mass and component species obtained at a monitoring site located at Tsinghua University, Beijing. In general, the agreement between modeled and observed data was good, and the model was able to capture the trends

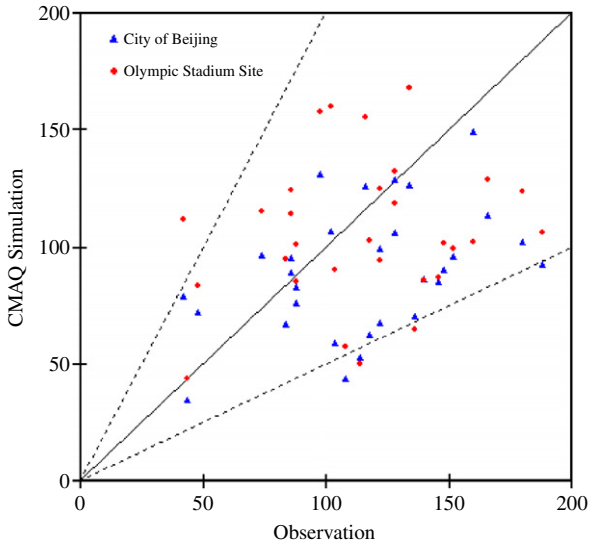

Fig. 3. Comparison of CMAQ model simulations for PM_{10} concentrations in the City of Beijing and at the Olympic Stadium site against observations derived from API data.

Table 2
Emissions of major anthropogenic species in the study region in July 2001

Region	Area (10^4 ha)[a]	Anthropogenic emissions (Gg mo^{-1})								
		SO_2	NO_x	CO_2[b]	CO	CH_4	NMVOC	NH_3	PM_{10}	$PM_{2.5}$
Beijing Municipality	164	26.5	17.7	5.29	195	17.2	28.3	12.5	5.50	2.27
Tianjin Municipality	119	34.1	22.7	4.79	142	15.0	22.7	9.91	6.71	2.63
Hebei Province	1884	106	58.7	18.7	545	155	72.0	151	38.6	16.6
Shandong Province	1571	154	66.7	19.4	534	192	90.6	164	48.0	22.8
Shanxi Province	1567	114	45.2	12.8	265	136	33.4	26.6	13.6	4.99
Regional total ($\div 10^3$)		435	211	61	1680	515	247	365	112	49
All China ($\div 10^3$)[c]		1699	946	318	9646	3196	1453	1131		
Regional share (%)		26	22	19	17	16	17	32		

[a]From China Statistical Yearbook (2004).
[b]Emissions in Tg mo^{-1}.
[c]One-twelfth of annual emissions (no monthly variation included) for 2000 (Streets et al., 2003). PM_{10} and $PM_{2.5}$ emissions were not reported in that work.

of daily and weekly variations of $PM_{2.5}$ and PM_{10}. The model slightly under-predicted $PM_{2.5}$ and PM_{10} concentrations, which might be due to an underestimation of local emissions but could be a model resolution issue; observations are based on a sparse set of point measurements, whereas model simulations are based on a volume average over unit grid cells. The performance of MM5 was also tested against wind and temperature data for the city of Beijing with good results. Temperature simulations, which are particularly important for ozone prediction, agreed within $<5\%$. However, for the time being, very limited ozone measurement data are available for July 2001 to conduct further model evaluations. Because ozone and $PM_{2.5}$ are such critical pollutants for human health, we recommend routine observations in cities like Beijing, so that their formation can be better understood, their spatial and temporal extent modeled with confidence, and effective mitigation measures designed.

4. Results

The model was used to simulate $PM_{2.5}$ and ozone concentrations in Beijing and surrounding areas. Fig. 4 (top two frames) shows base-case simulations of concentrations in the 4-km model domain. A second model case was run in which all man-made emissions in Beijing were removed (natural emissions such as biogenic VOC emissions were not removed). The resulting $PM_{2.5}$ and ozone concentrations are shown in the center two frames of Fig. 4. These two center frames can be considered to represent the contributions of sources outside Beijing to concentrations inside Beijing. The differences between these two sets of runs (shown in the bottom two frames) can be used to approximately represent the contributions of Beijing sources alone. Note that this approach cannot accurately reflect the contributions of Beijing sources alone, due to the non-linearity of model response to emission changes, especially for ozone.

Fig. 4 shows that monthly average $PM_{2.5}$ concentrations under base-case conditions are in excess of $30\,\mu g\,m^{-3}$ over most of the Beijing Municipality, rising to $>70\,\mu g\,m^{-3}$ in the Beijing urban center. The steep concentration gradients reveal the important role of local urban sources in determining the ambient $PM_{2.5}$ level. Sources outside Beijing (center left frame of Fig. 4) contribute a consistent level of $>20\,\mu g\,m^{-3}$ to Beijing $PM_{2.5}$ levels. The contribution of Beijing sources alone is $>30\,\mu g\,m^{-3}$ over a wide area of urban Beijing and $>60\,\mu g\,m^{-3}$ in the city center. Ozone shows a broader and more spatially variable signature than $PM_{2.5}$. Under base-case conditions, maximum hourly ozone concentrations are >90 ppb for much of the area comprising Beijing, Tianjin, and adjacent Hebei Province. The center right frame of Fig. 4 shows that ozone concentrations can be 60–90 ppb even with man-made Beijing emissions removed.

Based on very limited observational data for ozone in Beijing, we believe that the predicted concentrations of ozone in Beijing may be slightly underestimated. This may be due to an underestimation of VOC emissions—either anthropogenic (Streets et al., 2003) or biogenic (see Palmer et al., 2003). For example, modeled VOC/NO_x ratios in Beijing in this study are typically about six, whereas ratios in the US are typically 10–15 (Kang et al., 2004). On the other hand, an underestimation of CO emissions may be responsible (Streets et al., 2006) on the evidence that oxidation of CO is thought to be the largest source of ozone in eastern China (Tie et al., 2006). Improved regional emission inventories are needed to answer these questions.

In order to examine the implications for the Olympic Games, daily average concentrations of $PM_{2.5}$ and maximum hourly ozone concentrations were extracted from the model for the grid cell in which the Olympic Stadium is located. (The site of the Olympic Stadium is between the fourth and fifth ring roads, due north of the city center.) For each day of the month, concentrations resulting from the inclusion of emissions from all sources are contrasted with those for which man-made emissions from Beijing sources are removed (Fig. 5). For the Olympic Stadium site, the average of the simulated daily $PM_{2.5}$ concentrations is $77\,\mu g\,m^{-3}$ (range of $27–130\,\mu g\,m^{-3}$) for all sources and $26\,\mu g\,m^{-3}$ ($2–60\,\mu g\,m^{-3}$) for the contribution from sources outside Beijing. These results suggest that sources outside Beijing contribute, on average, about 34% of the measured $PM_{2.5}$ in the vicinity of the site of the Olympic Games in summertime. The July 2001 simulations show that $PM_{2.5}$ concentrations exceeded the US NAAQS for $PM_{2.5}$ ($65\,\mu g\,m^{-3}$) on many days (highest values of 130 and $115\,\mu g\,m^{-3}$); and, even when all Beijing sources were removed, the highest daily averages in the month (56 and $60\,\mu g\,m^{-3}$) were close to the US standard. (Recall that China has no $PM_{2.5}$ standard.)

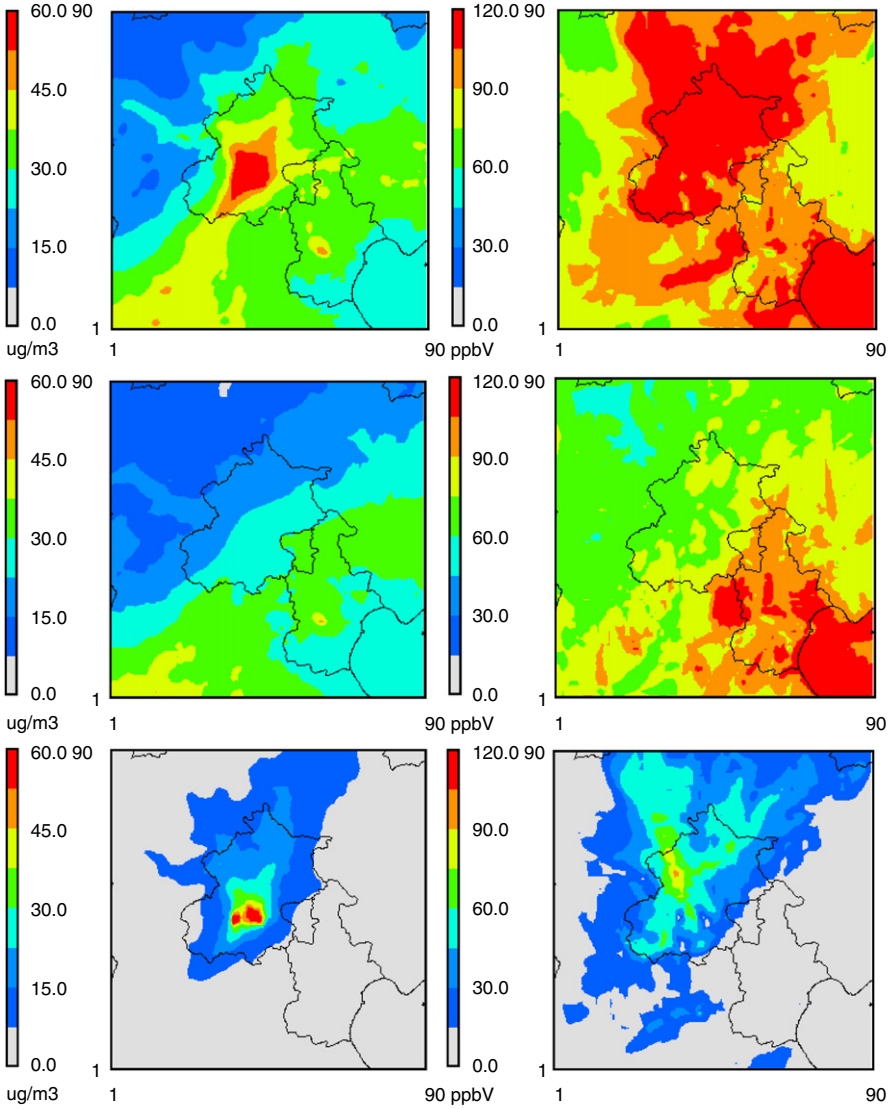

Fig. 4. CMAQ model simulations of monthly average concentrations of $PM_{2.5}$ (left) and maximum hourly concentrations of ozone (right) in the Beijing area for July 2001. Top frames show simulations for emissions from all sources; center frames show contributions from sources outside Beijing (Beijing emissions removed); bottom frames show the differences between top and center frames, which may be considered to approximately represent the contributions from Beijing sources alone (see text).

The ozone simulations show that maximum hourly ozone concentrations exceeded the China Grade II standard of ~100 ppb for one episode at the Olympic Stadium (July 6, 117 ppb) and came very close to 100 ppb on two other occasions (July 15 and 20). The influence of regional sources is more pronounced than for $PM_{2.5}$ and more complex. Simulations show considerable day-to-day fluctuation of maximum hourly ozone concentrations within a range of ~20–120 ppb. Simulations with Beijing man-made emissions removed show more stable values of ~50–80 ppb, reflecting the large-scale buildup of ozone in eastern China during the summertime (Mauzerall et al., 2000; Luo et al., 2000). When ozone concentrations are high (i.e., July 6, 10, 11, 15, 20, and 25), the contribution of regional sources is in the range of 30–70% at the Olympic Stadium site, depending on the assumed value of the global background ozone concentration. Fig. 6 shows the sensitivity of the regional contributions on those six days to global background concentrations in the range of 25–45 ppb. We choose 40 ppb as the most likely value, based on US EPA's modeling guidance and analysis by Tie et

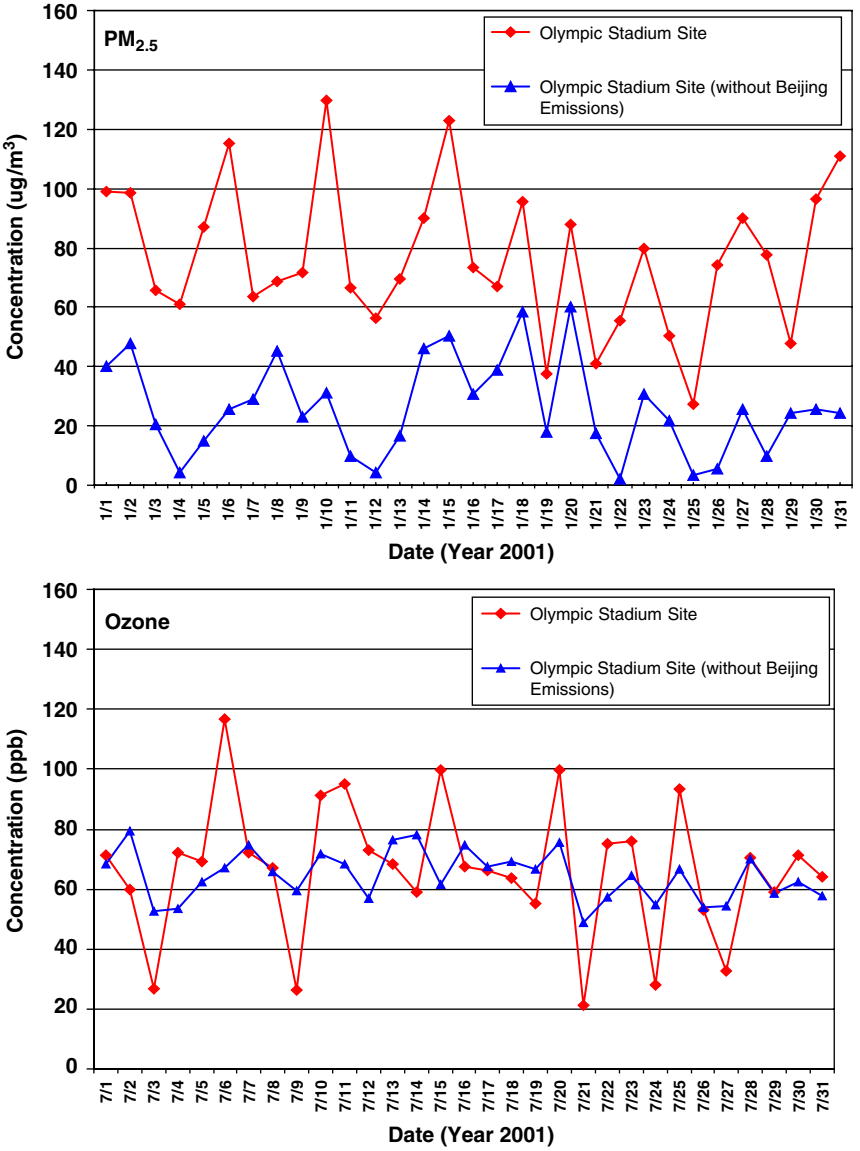

Fig. 5. CMAQ model simulations of daily average $PM_{2.5}$ concentrations and maximum hourly ozone concentrations at the Olympic Stadium site in Beijing for July 2001.

al. (2006) of ozone concentrations in eastern China; assuming 40 ppb, the regional contribution is 35–60%. Note that the regional contribution is not correlated with the magnitude of the ozone concentration.

For a number of days (notably July 3, 9, 21, 24, and 27), the model simulates higher ozone concentrations when man-made Beijing emissions are removed. This phenomenon is often observed in urban environments, when intense NO_x emissions from local sources titrate, or consume, ozone under certain meteorological conditions, and reflects the non-linear nature of model response to emission changes. In such situations, instead of lowering ozone concentrations, reduction of NO_x emissions can lead to higher ozone concentrations, sometimes referred to as a NO_x "disbenefit."

In order to give guidance to China's national and local policymakers, we ran four additional cases designed to elicit information on which surrounding areas influence Beijing's air quality the most in a typical summer month. These runs integrate the emission characteristics of the neighboring source regions (e.g., Taiyuan has many poorly controlled

high-sulfur coal-burning factories, whereas Shijiazhuang is a center of the chemicals industry with high VOC emissions) with important meteorological and topographical factors (e.g., Beijing is framed by hills to the north and west, as shown in Fig. 1). We ran the four cases by eliminating all man-made emissions, one region at a time, from Hebei Province, Tianjin Municipality, Shandong Province, and Shanxi Province. Table 2 shows that $PM_{2.5}$ emissions from Hebei and Shandong Provinces are 7–10 times larger than Beijing's, while PM emissions in Shanxi Province are about double Beijing's and Tianjin has about the same emissions. On an areal basis (Mg 10^{-3} ha^{-1} mo^{-1}), however, $PM_{2.5}$ emissions are comparable: Beijing 1.38, Tianjin 2.21, Hebei 0.88, Shandong 1.45, and Shanxi 0.32. With regard to ozone precursor emissions, the surrounding provinces are less dominant. Emissions of NO_x and VOC relative to Beijing emissions are 2–4 times for Hebei Province and Shandong Province, 1–3 times for Shanxi Province, and about the same for Tianjin.

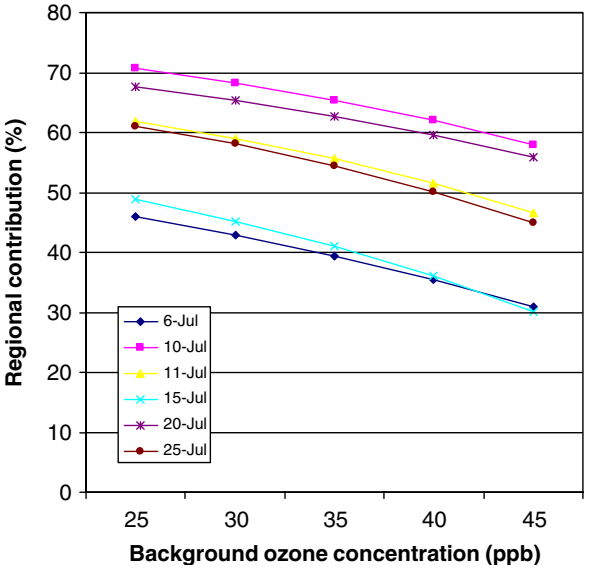

Fig. 6. Sensitivity of the regional source contribution to ozone concentrations at the Olympic Stadium site, as a function of the assumed level of background ozone concentration.

Fig. 7 shows two examples of the spatial variation of model-simulated percentage contributions of emissions in Tianjin and Hebei Province to monthly average $PM_{2.5}$ and peak ozone concentrations in Beijing. Note that these runs were performed at 12-km resolution throughout the east China domain. For $PM_{2.5}$, it can be seen that Hebei Province contributes 30% or more throughout the Beijing Municipality, whereas Tianjin's contribution

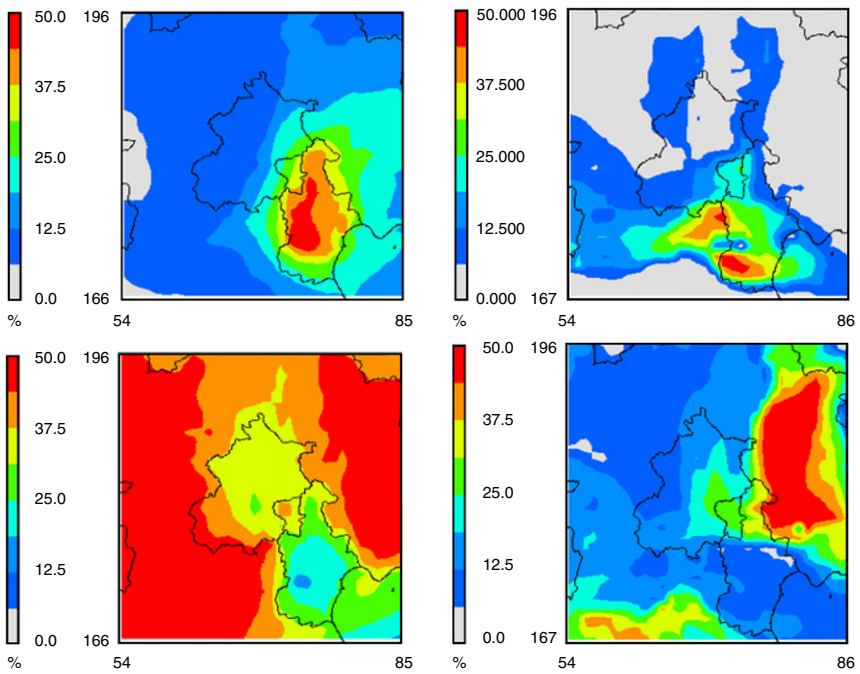

Fig. 7. Contribution of emissions (%) in neighboring provinces to monthly average $PM_{2.5}$ concentrations (left) and peak ozone concentrations (right) in Beijing, according to CMAQ model simulations for July 2001. Top: Tianjin; bottom: Hebei.

averages 10–20%, mostly to the eastern part of the Beijing Municipality. For ozone, the contributions are lower, with Hebei Province contributing on average 10–20% to ozone concentrations in the eastern part of Beijing and Tianjin's contribution being less than 10% for most of Beijing.

Fig. 8 shows the contributions of each of the four provinces to Beijing $PM_{2.5}$ and ozone concentrations for each day of the month of July. Each province's contribution varies dramatically from day to day, depending on wind direction and other meteorological factors. Modeled wind arrows in Fig. 8 show the wind strength and direction every 6 h at the Olympic Stadium site. It is clear that the dominant wind direction in July is from the south. The peak contributions from Hebei Province (e.g., $PM_{2.5}$ on July 29) and from Tianjin and Shandong Province (e.g., ozone on July 24) are preceded by several days of persistent wind from the south and southeast; in contrast, the low contributions from each of the four provinces on July 6 are preceded by dominant winds out of the northeast. Hebei Province shows the greatest contribution to $PM_{2.5}$ concentrations in Beijing, reaching as high as 70% and averaging 32% for the entire month. Under certain meteorological conditions, Shandong

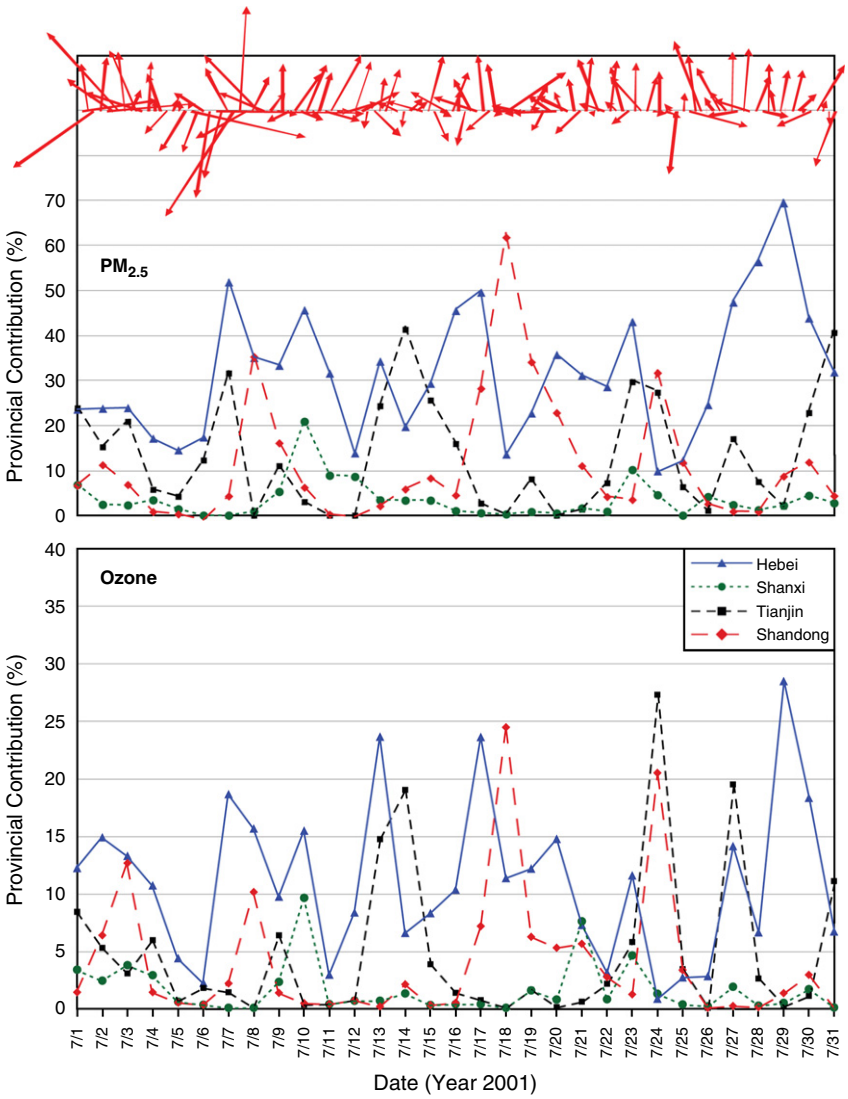

Fig. 8. CMAQ model simulations of the contributions of neighboring provinces to daily average $PM_{2.5}$ (upper) and maximum hourly ozone (lower) concentrations at the Olympic Stadium site in Beijing for July 2001. Also shown are modeled 6-hour wind arrows for the Olympic Stadium site.

Province (highest contribution 63%, average 11%) and Tianjin Municipality (highest contribution 42%, average 13%) also exert a significant influence. Shanxi Province, due to meteorological and topographical factors, shows less effect (maximum contribution 21%, average 3.5%). The influences on ozone concentrations are less pronounced, with maximum contributions of 28% for Hebei Province, 27% for Tianjin Municipality, 24% for Shandong Province, and 10% for Shanxi Province (but not at the same time). Because of the wide day-to-day fluctuations in the contributions to ozone concentrations, we do not present average values for ozone.

Limited modeling studies by Chinese researchers of ozone formation in the Beijing area have reached similar conclusions (Wang and Li, 2002, 2003). Wang and Li (2002) used the CAMx model to study the contributions of anthropogenic hydrocarbons to ozone formation in urban and suburban Beijing. They found that prevailing winds in summer daytime are from the south and southeast and that there is a definite regional contribution to both peak and average ozone concentrations in Beijing. Wang and Li (2003) found that emissions in Tianjin contributed 10–33% of the ozone in Beijing, while emissions in Hebei Province contributed 6–13%. Shandong and Shanxi Provinces had little contribution during the 2-day period of their simulations. Tang (2004) confirmed these results for a single day of Wang and Li's simulation (2003), reporting that emissions in Tianjin contributed 33% to ozone formation in downtown Beijing, while emissions in the southern part of Hebei Province contributed 11%. The weight of evidence from all model simulations is that the regional contribution to Beijing's air quality is almost always significant in the summertime and sometimes very large.

Cities like Beijing are trying hard to improve environmental controls and reduce emissions in the face of rapid economic development. By the beginning of the 21st century, Beijing had implemented a number of measures to improve air quality: increasing access to natural gas, electricity, and geothermal energy; converting all coal-burning stoves and residential boilers to cleaner energy; and enforcing more stringent emission standards for vehicles (BOCOG, 2004). This resulted in a decline in measured SO_2 and TSP concentrations—though values still exceeded Grade II standards, and NO_x levels were generally on the rise (Hao and Wang, 2005). Now China has announced further major renovation and restructuring programs in Beijing aimed at meeting the national standards by 2008, including reducing coal consumption, installing emission control equipment, increasing natural gas use, tightening vehicle emission standards, and introducing airborne PM and evaporative VOC controls. The specific objectives for the Olympic Games period are (a) that concentrations of SO_2, NO_2, and O_3 should meet WHO guidelines; and (b) that particle concentrations should be comparable to levels in major cities in the developed countries (BOCOG, 2004).

5. Conclusions

There is no doubt that the measures planned to limit air pollution in Beijing will greatly improve Beijing's air quality for the period of the 2008 Olympic Games. But will they be sufficient to achieve the stated objectives? This study shows that, even in the limit that Beijing generates no man-made emissions, levels of fine PM and ozone could still be high and could exceed healthful levels under unfavorable meteorological conditions. Because the limit of zero emissions cannot be achieved in practice, and because China is presently undergoing tremendous economic growth, the threat of higher regional emissions and higher concentrations of fine PM and ozone by 2008 is very real.

Air quality in Beijing in the summertime is dictated by meteorology and topography. Typically, temperatures are high, humidity is high, wind speeds are low, and the surrounding hills restrict venting of pollution. Thus, regional pollutants like $PM_{2.5}$ and ozone build up over several days—usually until dispersed by wind or removed by rain. Our modeling suggests that emission sources far from Beijing exert a significant influence on Beijing's air quality. We recommend new measurement and modeling studies to further investigate the nature of regional air quality in China, as well as the consideration of additional emission control measures for Beijing's neighboring provinces in plans for healthful air during the 2008 Olympic Games.

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