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Atmospheric Particulate Matter Pollution during the 2008 Beijing Olympics

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Abstract

Size fractionated particulate matter (PM) samples (including PM_{2.5} and PM₁₀) were collected at Peking University in Northwestern Beijing, China for a 2 week period prior to the Olympics, during the 2 week period of the Olympics, and for a 4 week period following the 2008 Olympics, during both source control and non-source control period. PM₁₀ concentrations in this study were high correlated with, but a factor of 1.3 times higher than, the Beijing Environmental Protection Bureau's PM₁₀ concentrations at near-by sites because of differences in the measurement methods used. The mean PM_{2.5} and PM₁₀ concentrations were statistically different, and lower by 31 and 35%, during the Olympic period compared to the non-Olympic period. However, the PM concentrations were not statistically different between the source control and non-source control periods. While meteorological parameters (air masses from the south and precipitation) accounted for 40% of the total variation in PM₁₀ concentration, source control accounted for 16%, suggesting that meteorology accounted for more of the variation in PM concentration than source control measures. The PM₁₀ concentrations in Beijing during the Olympic period were 2.9, 3.5, and 1.9 times higher than those in Atlanta, Sydney and Athens. In addition, the PM_{2.5} and PM₁₀ concentrations during the Olympic period exceeded the WHO 24-hour guideline 100% and 81% of the time, respectively. Finally, the PM₁₀ concentrations in October, November, and December 2008 were reduced by 9% to 27% compared to the same months in 2007, suggesting that the Olympic source control efforts (and possibly a down turn in the economy) have resulted in lower PM₁₀ concentrations in Beijing.

Introduction

Atmospheric particulate matter (PM) is composed of a mixture of various sized particles that have potentially toxic chemicals sorbed to them. These particles are mainly distributed in two fractions: fine particles (aerodynamic diameters <2.5μm) and coarse particles (aerodynamic diameters >2.5μm) (1,2). Fine particles are a concern for human lungs because they can be deposited more deeply in the lungs than coarse particles (2,3). Several studies have also shown that fine particles are linked to increased respiratory morbidity and mortality (2,3). Recently,

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Supporting Information Available

Details of the relative humidity correction of the quartz fiber filters, correlation analysis, a map of the Beijing sampling sites and calculated SRIFs are provided in the Supporting Information. This material is available free of charge via the Internet at <http://pubs.acs.org>.

Kan et al. (4) found that, in Shanghai, fine particles ($PM_{2.5}$) were associated with increased death rates from all causes, including cardiorespiratory diseases. In addition, PM-polluted air is believed to be responsible for about one million premature deaths per year in China (5).

Beijing ($39^{\circ}56'N$ and $116^{\circ}20'E$) is the capital of China with a population of over 17 million people and an area of 16,800 square kilometers. Beijing is surrounded by the Yanshan Mountains in the west, north and northeast which effectively trap air pollutants. In addition, the rapid urbanization and motorization of Beijing (1.39 million motor vehicles in 1999 compared to 3.3 million motor vehicles in 2007) has contributed to the high PM pollution in Beijing (2,6-11). Dust storm events in the spring, and re-suspended dust from traffic and construction activities, further exacerbate the PM pollution in Beijing (2).

Beijing hosted the 2008 Summer Games of the 29th Olympiad from August 8-24, 2008. In view of the significant air pollution in Beijing, the local governments cooperated to improve air quality during the 2008 Olympic Games. During the Olympic and the Paralympic Games, from July 20 to September 20, 2008, source control measures in Beijing included removing approximately one-half of the cars (~ 1.5 million cars) off the road on alternate days under an even-odd license plate system, closing pollution emitting factories, and slowing down construction activities. In the neighboring Tianjin municipality, Hebei, Shanxi and Shandong provinces, and Inner Mongolia Autonomous Region, polluting factories were closed and high-emission cars were removed from roads (12). In addition, in Beijing, stricter vehicle emission standards are being implemented, businesses are switching from coal power to natural gas, and heavy-duty truck traffic has gradually been reduced (12).

Given the significant international interest in improving the air quality of Beijing during the 2008 Olympic Games, some studies have attempted to predict the air quality during this period based on modeling (13,14). Using the US Environmental Protection Agency's Models-3/Community Multi-scale Air Quality (CMAQ) model over the Beijing region, Streets et al. (14) predicted that about 34% of $PM_{2.5}$ (on average) at the Olympic Stadium site can be attributed to sources outside of Beijing. The UNEP recently released an environmental assessment report of the Beijing 2008 Olympics games, including an assessment of air quality, which suggests that PM_{10} concentration was reduced by 20% during the source control periods (15). Although not at ground level, the interpretation of satellite-retrieved aerosol optical thickness for the Beijing region during the Olympic period suggests that the magnitude of aerosol load reduction during this period was low (10 to 15%) compared to meteorological variability (16).

The objectives of this study were to: (1) determine Beijing's atmospheric PM pollution during the Olympic and non-Olympic periods, as well as source control and non-source control periods; (2) assess the influence of meteorology on PM concentrations; and (3) determine the source regions that influenced Beijing's PM concentrations and the effectiveness of source control strategies in reducing PM pollution.

Materials and Methods

Sampling

The sampling site was located on the roof of the 7-story Geology Building on the Peking University (PKU) campus, about 25 meters above ground. PKU is located in northwestern Beijing and is primarily a residential and commercial area without major industrial sources (Figure SI.1). Local PM emission sources within 1 km of PKU include vehicular traffic, fuel combustion for domestic cooking and heating, and construction. The 2008 Olympic table tennis, marathon, and bicycle races were held on or near the PKU campus.

PM was collected and size fractionated using a three stage High Volume Cascade Impactor (Series 230, Tisch Environmental, Cleves, OH) that operated in accordance with procedures established by USEPA (CFR40, Part 50.11, Appendix B, July 1, 1975, pages 12-16) and ASTM Specification D2009. The Impactor stages consisted of two aluminum plates, with outside dimensions of 6 inches $\times$ 7 inches that held 5.625 inch $\times$ 5.375 inch filters with ten perforated slots, and a base aluminum plate that held an 8 $\times$ 10 inch filter. The High Volume Cascade Impactor was calibrated according to the manufacturer's instructions before use and once per week during the sampling periods. Airborne particles were size fractionated based on their aerodynamic particle diameter and are abbreviated as follows: $<2.5\mu\text{m}$ ($\text{PM}_{2.5}$) (bottom 8 inch $\times$ 10 inch filter), $2.5\text{--}10\mu\text{m}$ ($\text{PM}_{2.5\text{--}10}$) (middle 5.625 inch $\times$ 5.375 inch filter), and $>10\mu\text{m}$ ($<\text{PM}_{10}$) (top 5.625 inch $\times$ 5.375 inch filter). We calculated the PM_{10} concentration by summing the $\text{PM}_{2.5}$ and $\text{PM}_{2.5\text{--}10}$ concentrations.

Sixty-three sets of size fractionated PM samples were collected continuously over 24 h periods ($\sim 1500\text{ m}^3$) from July 28 to September 3, 2008 and from September 13 to October 7, 2008. Six field blanks were also collected during these periods. Samples were not collected from September 4 to 12, 2008 because of sampler motor failure. Quartz fiber filters (Tisch Environmental, Cleves, OH), that were baked in a furnace at 350°C prior to use, were used for sample collection and were weighed before and after sample collection.

A subset of the filters ($\sim 33\%$) was weighed before and after sample collection, and before and after dessication for 24 hours, in accordance with USEPA Method 5 of 40 CFR Part 60 (<http://www.epa.gov/ttn/emc/methods/method5.html>). The percent change in filter mass due to dessication (0 to 20%) was correlated with the ambient relative humidity (40 to 95%) during the sample collection period and this relationship was used to correct the change in filter mass (see Supporting Information). Only a subset of samples was tested by dessication and the filters were not dried at 105°C after sample collection in order to minimize analyte loss and/or sample contamination that would affect subsequent semi-volatile organic compound analysis of the filters. Detailed information on the filter mass humidity correction is given in the Supporting Information (Figure SI.2).

Meteorological Data

Meteorological data, including wind speed (WS), wind direction (WD), precipitation (Precip), atmospheric pressure (P), temperature (T), and relative humidity (RH), were simultaneously measured every minute by HOBO Auto Meteorological Station (Onset Company, Pocasset, MA) at the sampling site during all sample collection periods.

Beijing Air Pollution Index PM_{10} Data

The Beijing Environmental Protection Bureau's (Beijing EPB's) Air Pollution Index (API) PM_{10} data was used for comparison. The Beijing EPB's PM_{10} measurements were made continuously using Tapered Element Oscillating Microbalances (TEOM® RP1400a) as described in USEPA Method IO-1.3 of EPA/625/R-96/010a (<http://www.epa.gov/ttn/amtic/inorg.html>). We compared our PKU data to the Beijing EPB's data at the following sites: the WanLiu (WL) PM_{10} Auto-monitoring Station (located 3 km from our PKU air monitoring site); the Olympic Center (OC) PM_{10} Auto-monitoring Station (located 3 km from our PKU site), the Beijing Average API data (the average from all Beijing EPB sites shown in Figure SI.1), and the average API data for all of the urban Beijing EPB sites within the 5-Ring Road of Beijing (Figure SI.1). The Beijing EPB's API PM_{10} values were converted to PM_{10} concentrations (Con_{WL} , Con_{OC} , $\text{Con}_{\text{Beijing}}$ and $\text{Con}_{5\text{-Ring}}$) in $\mu\text{g}/\text{m}^3$ as described in reference 17. $\text{PM}_{2.5}$ concentrations were not reported by the Beijing EPB during this period so no comparison could be made to our PKU $\text{PM}_{2.5}$ concentrations.

Air Mass Back Trajectories and Data analysis

Four-day air mass back trajectories were calculated using National Oceanic and Atmospheric Administration (NOAA)'s ARL HYSPLIT 4.0 model (with meteorological data from the Global Data Assimilation System, GDAS) (18). For each 24 h sample, seven trajectories were calculated (one every 4 h), including the sample start and stop times. The trajectories were calculated at 50, 150, 250 and 350 m asl and S-PLUS version 8.0 (insightful, Seattle, WA) was used for statistical analysis.

Results and Discussion

Comparison of PKU and Beijing EPB PM Data

We chose to compare our PKU PM₁₀ concentrations to the Beijing EPB PM₁₀ concentrations measured at the WanLiu PM₁₀ Auto-monitoring station (Con_{WL}) because of its close proximity to our PKU site and the Olympics Center PM₁₀ Auto-monitoring station (Con_{OC}) because of its proximity to many Olympic events. In addition, we compared our PKU PM₁₀ concentrations to the Beijing average PM₁₀ concentrations (Con_{Beijing}) reported by the Beijing EPB and the more urban Beijing EPB sites within the 5-Ring Road of Beijing (Con_{5-Ring}).

There was significant correlation ($p < 0.001$) between the PKU PM_{2.5} and PM₁₀ concentrations (Table SI.1). In addition, there was significant correlation ($p < 0.001$) between our PKU PM₁₀ concentrations and the Beijing EPB PM₁₀ concentrations at the WanLiu and Olympic Center sites, as well as the average PM₁₀ concentrations for Beijing and the PM₁₀ concentrations within the 5-Ring Road (Table SI.1 and Figure SI.3). However, our PKU PM₁₀ concentrations were a factor of 1.3 times higher than the Beijing EPB PM₁₀ concentrations for all comparison sites (Figure SI. 3). A factor of 1.3 between gravimetric PM₁₀ methods and TEOM methods has been previously reported and is likely due to the loss of volatile and semi-volatile components of the PM during the TEOM measurement (19-21).

Comparison of Olympic and Non-Olympic Periods

The mean PKU PM_{2.5} and PM₁₀ concentrations and Beijing EPB PM₁₀ concentrations during the Olympic and non-Olympic periods are given in Table 1. In addition, Figure 1 shows the temporal variation in the PKU PM_{2.5} and PM₁₀ concentrations. Our 2008 PKU PM_{2.5} and PM₁₀ concentrations are comparable to, or slightly lower than, previously reported concentrations in Beijing (including previous measurements at PKU) (6-11)

The mean PKU PM_{2.5} and PM₁₀ concentrations during the Olympic period were significantly different and 31% to 35% lower than the PM concentrations measured during the non-Olympic period (Table 1). In addition, the mean PKU >PM₁₀ and PM_{2.5-10} concentrations were reduced by 42%, while the PM_{2.5} concentrations were reduced by only 31%.

Based on the PKU PM₁₀ concentration for individual days during the Olympic period, 12% of days exceeded the U.S. National Ambient Air Quality Standard (NAAQS) (150 µg/m³) for a 24-hour period and China's Ambient Air Quality Standard (CAAQS) for cities (grade II 150 µg/m³) and 81% of days exceeded the WHO 24-hour PM₁₀ air quality guideline (AQG) (50 µg/m³) and CAAQS Grade I (Table SI.2). Based on the Beijing average EPB PM₁₀ concentration for individual days during the Olympic period, no days exceeded the NAAQS and CAAQS grade II and 44% of days exceeded the WHO AQG and CAAQS Grade I. However, based on the PKU PM_{2.5} concentration for individual days during the Olympic period, 88% of days exceed the U.S. NAAQS (35 µg/m³) and 100% of days exceeded the WHO AQG (25 µg/m³) (Table SI.2)

The mean $PM_{2.5}/PM_{10}$ ratio was not significantly different between the Olympic (0.77) and non-Olympic (0.75) periods (Table 1). Our results indicate that fine particles ($PM_{2.5}$) accounted for 62 – 86% of the inhalable particles and were the major component of the PM_{10} concentrations. Previous studies measured a $PM_{2.5}/PM_{10}$ ratio of 0.25 to 0.88 in Beijing (2). High $PM_{2.5}/PM_{10}$ ratios (larger than 0.6) are generally attributed to NO_3^- , SO_4^{2-} and NH_4^+ and secondary organic aerosols, while low ratios are attributed to soil or construction dust (2). Although Beijing's PM concentrations were significantly reduced during the Olympic period, the similarity of the $PM_{2.5}/PM_{10}$ ratio during the Olympic and non-Olympic periods suggests that combustion sources were a significant contributor to PM concentrations during both periods.

Comparison of Source Control and Non-Source Control Periods

Although it is interesting to compare the PM concentrations during the Olympic and non-Olympic periods from an athlete and spectator health standpoint, a comparison of the source control and non-source control periods is more relevant from an atmospheric chemistry standpoint. The mean PKU $PM_{2.5}$ and PM_{10} concentrations and Beijing EPB PM_{10} concentrations (Con_{WL} , Con_{OC} , and $Con_{Beijing}$) during the source control and non-source control periods are given in Table 2. Figure 1 shows that some of the lowest PM concentrations were measured during the non-source control period, while some of the highest PM concentrations were measured during the source control period. This suggests that factors other than source control, such as meteorological conditions, were important in determining the day-to-day variation in Beijing's PM concentrations.

Unlike the Olympic and non-Olympic periods, only the mean PKU $PM_{2.5-10}$ concentration was significantly different between the source control and non-source control periods, with a 31.2% reduction in concentration (Table 2). Similar to the Olympic and non-Olympic periods, the source control measures were less effective at reducing $PM_{2.5}$ concentrations than $>PM_{10}$ and $PM_{2.5-10}$ concentrations.

The mean PKU $PM_{2.5}$ and PM_{10} concentrations during the Olympic period were significantly different, and 16.9% to 26.3% lower, than during the source control periods before and after the Olympic period (Tables 1 and 2). This suggests that additional source control measures may have been taken during the Olympic period. Overall, the mean PM concentrations were Olympic period < source control period < non-Olympic period < non-source control period.

Based on the PKU PM_{10} concentration for individual days during the source control period, 22% of days exceed the NAAQS and CAAQS Grade II and 88% of days exceeded the WHO AQG and CAAQS Grade I. Based on the Beijing average EPB PM_{10} concentration during the source control period, 7% of days exceeded the NAAQS and CAAQS grade II and 68% of days exceeded the WHO AQG and CAAQS Grade I. Based on the PKU $PM_{2.5}$ data for individual days, 93% of days exceed the NAAQS and 100% of days exceeded the WHO AQG during the source control period.

Finally, similar to the Olympic and non-Olympic periods, the $PM_{2.5}/PM_{10}$ ratio was not significantly different between the source control (0.76) and non-source control (0.75) periods (Table 2) and was similar to the Olympic and non-Olympic periods (Table 1). These results suggest that the source control measures had little effect on the proportion of PM that was highly respirable ($PM_{2.5}$).

Identification of PM Source Regions to Beijing

Although PM sources in Beijing clearly contribute to PM concentrations in the city, it has been shown that surrounding areas also contribute to Beijing's PM concentrations (14,15). Four day

air mass back trajectories were calculated for each air mass sampled at PKU and were used to determine the impact of different source regions on Beijing PM concentration. These source region impact factors (SRIFs) represents the percentage of time an air mass spent in a given source region (Northeast, Northwest, South and East of Beijing) in the last 4 days prior to arrival in Beijing. The higher the SRIF percentage, the more time the sampled air mass spent in a given source region. Details of the SRIF calculation are reported elsewhere (22).

The four potential source regions to Beijing, South (SRIF_{South}), Northeast (SRIF_{Northeast}), Northwest (SRIF_{Northwest}) and East (SRIF_{East}) of Beijing, and representative 4-day air mass back trajectories are shown in Figure 2. The correlations between the PKU PM_{2.5} and PM₁₀ concentrations and the Beijing EPB PM₁₀ concentrations (Con_{WL}, Con_{OC}, and Con_{Beijing}) and air mass SRIFs were calculated to determine if changes in Beijing PM concentrations were significantly correlated with air mass time in different source regions (Table SI.3). If a source region had a significant influence on Beijing's PM concentration, then a significant correlation would exist. For the entire dataset (both source control and non-source control periods), there was a significant positive correlation between PM concentrations and SRIF_{South} and a significant negative correlation between PM concentrations and SRIF_{Northwest} (Figure SI.4). This suggests that air masses from regions south of Beijing, including Hebei, Shandong, Shanxi and Tianjin, increased PM concentrations in Beijing, while air masses from regions northwest of Beijing, including Russia and Mongolia, decreased PM concentrations in Beijing. Other researchers have also shown that the area south of Beijing was a source for PM pollution to Beijing (14-16).

Influence of Meteorology

The correlation between PM concentration and meteorology (including wind speed, wind direction, temperature, precipitation, and relative humidity) was investigated (Table SI.4). The precipitation amount (on the day prior to the air sampling day), was significantly negatively correlated with PM concentration due to wet deposition ($p < 0.01$) (Table SI.4). The relative humidity (excluding the days with precipitation) was significantly positively correlated with PM concentration ($p < 0.05$) (Table SI.4) and SRIF_{South} ($p < 0.05$) (Table SI.4). High relative humidity can promote the formation of secondary organic aerosols (7,23). In addition, all PM concentrations (excluding $>PM_{10}$) were significantly positively correlated ($p\text{-value} < 0.01$) with wind from the south, and significantly negatively correlated ($p\text{-value} < 0.05$) with winds from the north. This is consistent with our interpretation of SRIFs discussed above.

To assess the impact of meteorological conditions, in addition to the source control measures, on PM concentrations, a multivariable linear regression (MLR) model was developed. MLR models have been previously used to assess the effect of meteorological conditions on PM and other pollutant concentrations (22,24,25).

Autocorrelation was used to reduce the number of meteorological parameters for the MLR model. Because there was significant autocorrelation between SRIF_{South}, relative humidity, and wind direction (Table SI.4), only SRIF_{South} was used in the MLR model. In addition, to describe the varying levels of source control during the sampling period, indicator variables were used to describe the Olympic, Source Control (non-Olympic) and Non-Source Control periods:

$$C_{PM} = \beta_0 + \beta_1 SRIF_{South} + \beta_2 Precip + (\beta_3 Oly + \beta_4 SC_{nonOly} + \beta_5 NSC)$$

Where C_{PM} is the PM concentration for the entire dataset, $SRIF_{South}$ is SRIF from the south of Beijing, $Precip$ (mm/day) is the precipitation amount for the day prior to the sampling day, Oly is indicator variable for the Olympic period (coded "1" for an "Olympic" day and "0" for

all other days), SC_{nonOly} is the indicator variable for the Source Control period outside of the Olympic period (coded “1” for a “Source Control” day outside of the Olympic period and “0” for all other days), and NSC is the indicator variable for the Non-source Control period (coded “1” for a “Non-source Control” day and “0” for all other days).

The MLR model results are shown in Table SI.5. Meteorological parameters ($SRIF_{South}$ and precipitation) accounted for 40% of the total variation in PM_{10} concentration, while source control accounted for only 16%. The results were similar for $PM_{2.5}$ (Table SI.5). These data suggest that, at ground level, meteorology accounted for a larger portion of the variation in PM concentration than source control measures. Using an analysis of aerosol load from the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical thickness product for the Beijing region during the Olympic period, Cermak and Knutti (16) recently reported a statistically significant reduction in aerosol load that decreased in magnitude and significance with increasing region size. They also reported that the magnitude in aerosol load reduction was low (10 to 15%) compared to meteorological variability (16). Their findings are consistent with our findings at ground level and reflect the importance of PM emissions and transport on a regional scale in controlling Beijing's PM pollution.

Comparison of PM_{10} Concentration to Other Olympic Cities

Table SI. 6 summarizes the PM_{10} concentrations in Beijing, China, Atlanta, Georgia, Sydney, Australia, and Athens, Greece one month before, during, and after their respective Olympic Games (26-28). During the Olympic periods, the mean PM_{10} concentrations were $28.1 \mu\text{g}/\text{m}^3$, $23.7 \mu\text{g}/\text{m}^3$, $44.3 \mu\text{g}/\text{m}^3$, $82.4 \mu\text{g}/\text{m}^3$ and $53.7 \mu\text{g}/\text{m}^3$ in Atlanta, Sydney, Athens, PKU PM_{10} , and Beijing EPB average, respectively. The mean PM_{10} concentrations in Beijing were 1.9 to 3.5 times higher than the other three Olympic cities. Of these Olympic cities, only Beijing exceeded the WHO standard for PM_{10} . However, Beijing had the most significant decrease in PM_{10} concentrations (40%), compared to Atlanta (29% reduction), Sydney (72% increase), and Athens (9% decrease), during the Olympic period.

Post-Olympic PM_{10} Concentrations

Beijing PM concentrations are dependent on seasonal weather conditions and seasonal heating (8,11). As a result, PM concentrations are generally higher in the winter months (2). In order to evaluate the current status (post-Olympics) of PM concentrations in Beijing, and if the source control measures implemented during the Olympics were still effective, we compared the monthly mean Beijing EPB $Con_{Beijing}$ values for October, November and December 2007 and 2008 (Table SI.7). There was a 8.7%, 27.0% and 26.9% reduction in the mean $Con_{Beijing}$ concentration in October, November and December 2008, respectively, compared with the same 2007 periods (p value <0.1).

During the post-Olympic period, traffic was reduced by 20% and this, along with a down turn in the economy and energy production, appears to have resulted in a 9-27% decrease in PM_{10} concentrations compared to the end of 2007. However, the monthly mean Con_{WL} , Con_{OC} , and $Con_{Beijing}$ concentrations during October, November and December, 2008 were 47.9% to 65.5% higher than the PM_{10} concentrations during Olympic period and 30.5 to 52.7% higher than during the source control period.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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References

1. Finlayson-Pitts BJ, Pitts JN. Tropospheric air pollution: ozone, airborne toxics, polycyclic aromatic hydrocarbons, and particles. *Science* 1997;276:1045–1052. [PubMed: 9148793]
2. Chan CK, Yao X. Air pollution in mega cities in China. *Atmos. Environ* 2008;42:1–42.
3. Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA, J. Am. Med. Assoc* 2002;287:1132–1141.
4. Kan H, London SJ, Chen G, Zhang Y, Song G, Zhao N, Jiang L, Chen B. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. *Environ. Int* 2007;33:376–384. [PubMed: 17229464]
5. Florig HK, Sun G, Song G. Evolution of particulate regulation in China—prospects and challenges of exposure-based control. *Chemosphere* 2002;49:1163–1174. [PubMed: 12492170]
6. He K, Yang Y, Ma Y, Zhang Q, Yao X, Chan CK, Cadle S, Chan T, Mulawa P. The characteristics of PM_{2.5} in Beijing, China. *Atmos. Environ* 2001;35:4959–4970.
7. Sun YL, Zhuang GS, Tang AH, Wang Y, An ZS. Chemical Characteristics of PM_{2.5} and PM₁₀ in Haze-Fog Episodes in Beijing. *Environ. Sci. Technol* 2006;40:3148–3155. [PubMed: 16749674]
8. Duan FK, He K, Ma YL, Yang FM, Yu XC, Cadle SH, Chan T, Mulawa PA. Concentration and chemical characteristics of PM_{2.5} in Beijing, China: 2001–2002. *Sci. Total Environ* 2006;355:264–275. [PubMed: 16185747]
9. Bergin MH, Cass GR, Xu J, Fang C, Zeng LM, Yu T, Salmon LG, Kiang CS, Tang XY, Zhang YH, Chameides WL. Aerosol radiative, physical, and chemical properties in Beijing during June 1999. *J. Geophys. Res., [Atmos.]* 2001;106:17969–17980.
10. Chan CY, Xu XD, Li YS, Wong KH, Ding GA, Chan LY, Cheng XH. Characteristics of vertical profiles and sources of PM_{2.5}, PM₁₀ and carbonaceous aerosols in Beijing. *Atmos. Environ* 2005;39:5113–5124.
11. Zheng M, Salmon LG, Schauer JJ, Zeng L, Kiang CS, Zhang Y, Cass GR. Seasonal trends in PM_{2.5} source contributions in Beijing, China. *Atmos. Environ* 2005;39:3967–3976.
12. Stone R. Beijing's Marathon run to clean foul air nears finish line. *Science* 2008;321:636–637. [PubMed: 18669839]
13. Chen DS, Cheng SY, Liu L, Chen T, Guo XR. An integrated MM5-CMAQ modeling approach for assessing trans-boundary PM₁₀ contribution to the host city of 2008 Olympic summer games – Beijing, China. *Atmos. Environ* 2007;41:1237–1250.
14. Streets DG, Fu JS, Jang CJ, Hao JM, He KB, Tang XY, Zhang YH, Wang ZF, Li ZP, Zhang Q, Wang LT, Wang BY, Yu C. Air quality during the 2008 Beijing Olympic Games. *Atmos. Environ* 2007;41:480.
15. United Nations Environment Programme. Independent Environmental Assessment: Beijing 2008 Olympic Games. UNEP; Nairobi, Kenya: 2009.
16. Cermak J, Knutti R. Beijing Olympics as an aerosol field experiment. *Geophys. Res. Lett* 2009;36:L10806.doi: 10.1029/2009GL038572
17. Andrews SQ. Inconsistencies in air quality metrics: ‘Blue Sky’ days and PM₁₀ concentrations in Beijing. *Environ. Res. Lett* 2008;3:1–14.
18. Draxler, RR.; Rolph, GD. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory). NOAA Air Resources Laboratory; Silver Spring MD: 2003. <http://www.arl.noaa.gov/ready/hysplit4.html>

19. DETR. Assistance with the Review and Assessment of PM₁₀ Concentrations in Relation to the Proposed EU Stage 1 Limit Values. HMSO; London: 1999.
20. Airborne Particles expert group (APEG). Source Apportionment of Airborne Particulate Matter in the United Kingdom. DETR; 1999.
21. Green D, Fuller G, Barratt B. Evaluation of TEOM™ ‘correction factors’ for assessing the EU stage 1 limit values for PM₁₀. *Atmos. Environ* 2001;35:2589–2593.
22. Primbs T, Simonich S, Schmedding D, Wilson G, Jaffe D, Takami A, Kato S, Hatakeyama S, Kajii Y. Atmospheric Outflow of Anthropogenic Semivolatile Organic Compounds from East Asia in Spring 2004. *Environ. Sci. Technol* 2007;41:3551–3558. [PubMed: 17547177]
23. Kang CM, Lee HS, Kang BW, Lee SK, Sunwoo Y. Chemical characteristics of acidic gas pollutants and PM_{2.5} species during hazy episodes in Seoul, South Korea. *Atmos. Environ* 2004;38:4749–4760.
24. Hafner WD, Hites RA. Effects of wind and air trajectory directions on atmospheric concentrations of persistent organic pollutants near the great lakes. *Environ. Sci. Technol* 2005;39:7817–7825. [PubMed: 16295842]
25. Hien PD, Bac VT, Tham HC, Nhan DD, Vinh LD. Influence of meteorological conditions on PM_{2.5} and PM_{2.5–10} concentrations during the monsoon season in Hanoi, Vietnam. *Atmos. Environ* 2002;36:3473–3484.
26. PM₁₀ concentration in Atlanta during Olympic time in 1996. Air Protection Branch of EPA; Georgia: Available from
27. PM₁₀ concentration in Sydney during Olympic time in 2000. Available at <http://www.environment.nsw.gov.au/AQMS/aqi.htm>
28. PM₁₀ concentration in Athens during Olympic time in 2004. Available at <http://www.minenv.gr>

Figure 1.

Temporal variation of the PKU $PM_{2.5}$, $PM_{2.5-10}$, and PM_{10} concentrations and meteorological parameters. The source control, non-source control and the Olympic periods are separated by different background colors.

Figure 2.

The four defined source regions and representative 4-day air mass back trajectories. Northeast: 41-54 N, 120-135 E, on 17-Aug, 2008; Northwest: 41-65 N, 80-120 E, on 23-Sep, 2008; South: 30-41 N, 105-123 E, on 27-Aug, 2008; East: 30-41 N, 123-140 E, on 11-Aug, 2008. The two pictures were taken from the same position on the same day as the representative trajectory indicated.

Table 1

Concentration of PM during the Olympic and non-Olympic periods, t-test results, and the reduction in PM concentration.

	Olympic time (n=17)			Non-Olympic time (n=46)			T-test (p_value)	Reduction	
	Mean ($\pm$ sd)	Min.	Max.	Mean ($\pm$ sd)	Min.	Max.		Con.	(%)
>PM ₁₀ ($\mu\text{g}/\text{m}^3$)	12.6 $\pm$ 6.1	4.9	25.9	22.0 $\pm$ 14.4	3.8	60.3	0.015	9.4	42.70%
PM _{2.5-10} ($\mu\text{g}/\text{m}^3$)	17.7 $\pm$ 6.8	9.1	29.4	30.6 $\pm$ 17.5	6.6	80.7	0.006	12.9	42.12%
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	64.7 $\pm$ 36.3	28.2	147.4	93.9 $\pm$ 50.2	28.7	214.4	0.039	29.2	31.09%
PM ₁₀ ($\mu\text{g}/\text{m}^3$)	82.4 $\pm$ 42.4	37.4	174.6	124.5 $\pm$ 65.8	35.6	295.1	0.022	42.1	35.02%
R _{PM2.5/PM10}	0.77 $\pm$ 0.04	0.70	0.84	0.75 $\pm$ 0.05	0.62	0.86	0.264	-0.02	-2.67%
Con _{WL} ($\mu\text{g}/\text{m}^3$)	53.4 $\pm$ 26.4	20.0	106.0	86.8 $\pm$ 47.3	14.0	208.0	0.008	33.3	38.44%
Con _{OC} ($\mu\text{g}/\text{m}^3$)	54.6 $\pm$ 29.7	18.0	114.0	84.1 $\pm$ 49.5	15.0	208.0	0.025	29.5	35.07%
Con _{Beijing} ($\mu\text{g}/\text{m}^3$)	53.7 $\pm$ 28.3	17.0	114.0	82.6 $\pm$ 47.0	12.0	202.0	0.021	28.9	35.02%

Table 2

Concentration of PM during the source control and non-source control periods, t-test results, and the reduction in PM concentration.

	Source Control Time (n=46)			Non-Source Control Time (n=17)			T-test (p_value)	Reduction	
	Mean ($\pm$ sd)	Min.	Max.	Mean ($\pm$ sd)	Min.	Max.		Con.	(%)
>PM ₁₀ ($\mu\text{g}/\text{m}^3$)	17.6 $\pm$ 10.6	4.7	44.5	23.9 $\pm$ 18.3	3.8	60.3	0.112	6.3	26.44%
PM _{2.5-10} ($\mu\text{g}/\text{m}^3$)	24.0 $\pm$ 10.3	9.1	45.2	34.9 $\pm$ 25.3	6.6	80.7	0.025	10.9	31.23%
PM _{2.5} ($\mu\text{g}/\text{m}^3$)	81.3 $\pm$ 43.2	28.2	205.9	97.2 $\pm$ 59.8	28.7	214.4	0.277	15.9	16.39%
PM ₁₀ ($\mu\text{g}/\text{m}^3$)	105.3 $\pm$ 52.4	37.4	251.1	132.2 $\pm$ 83.8	35.6	295.1	0.158	26.9	20.32%
R _{PM2.5PM10}	0.76 $\pm$ 0.05	0.62	0.84	0.75 $\pm$ 0.06	0.64	0.86	0.506	-0.01	-1.33%
Con _{WL} ($\mu\text{g}/\text{m}^3$)	73.3 $\pm$ 37.6	20.0	170.0	89.9 $\pm$ 60.5	14.0	208.0	0.196	16.6	18.47%
Con _{OC} ($\mu\text{g}/\text{m}^3$)	73.0 $\pm$ 40.1	18.0	194.0	84.5 $\pm$ 61.9	15.0	208.0	0.392	11.4	13.56%
Con _{Beijing} ($\mu\text{g}/\text{m}^3$)	71.6 $\pm$ 38.0	17.0	170.0	83.2 $\pm$ 59.2	12.0	202.0	0.362	11.6	13.95%