

Impact of air pollution control measures and weather conditions on asthma during the 2008 Summer Olympic Games in Beijing

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Abstract The alternative transportation strategy implemented during the 2008 Summer Olympic Games in Beijing provided an opportunity to study the impact of the control measures and weather conditions on air quality and asthma morbidity. An ecological study compared the 41 days of the Olympic Games (8 August–17 September 2008) to a baseline period (1–30 June). Also, in order to emphasize the impact of weather conditions on air quality, a pollution linking meteorological index (Plam) was introduced to represent the air pollution meteorological condition. Our study showed that the average number of outpatient visits for asthma was 12.5 per day at baseline and 7.3 per day during the Olympics—a 41.6% overall decrease. Compared with the baseline, the Games were associated with a significant reduction in asthma visits (RR 0.58, 95%CI: 0.52–0.65). At 16.5 visits per day, asthma visits were also significantly higher, during the pre-Olympic period (RR 1.32, 95% CI: 1.15–1.52). The study also showed that the RR of asthma events on a given day, as well as the average daily peak ozone concentration during the preceding 48–72 h, increased at cumulative ozone concentrations of 70 to 100 ppb and 100 ppb or more compared with ozone concentrations of

less than 70 ppb ($P<0.05$). We concluded that along with “good” weather conditions, efforts to reduce traffic congestion in Beijing during the Olympic Games were associated with a prolonged reduction in air pollution and significantly lower rates of adult asthma events. These data provide support for efforts to reduce air pollution and improve health via reductions in motor vehicle traffic.

Keywords Air pollution · Asthma · Meteorological · Olympic Games

Introduction

Despite advances in asthma therapy, the morbidity of asthma continues to increase. This increase has been so rapid that it cannot be explained by genetic change. In China, asthma has an estimated prevalence of about 1–5%, and there are about 10–15 million asthma patients. According to a survey by the National Pediatric Asthma Collaborative Group, (National Pediatric Asthma Collaborative Group 1993, 2003), there was an increase in the prevalence of asthma in children of 64.84% from 1990 to 2000, and this trend was more significant in developed mega cities: in Beijing, this increase was 260%. Chongqing—the fastest growing city in recent years—has the highest prevalence, at 4.63%. In contrast, in cities with slow economic development, the prevalence is much lower: 0.57% in Lhasa (Tibet) and 0.25% in Xining (capital city of Qinghai Province). According to the estimation of doctors in large hospitals in Beijing and Shanghai (Chen 2006), asthma outpatients increased about 40% from 2000 to 2005, and about half of these were children. After 2006, this increase speeded up (Watts 2006).

The cause or causes of this phenomenon remain controversial. Experimental, laboratory, and epidemiologic

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studies in the last several years have linked high concentrations of known air pollutants to respiratory health problems, most notably exacerbations of asthma. However, opportunities to study the health effects of anthropogenic improvements in air quality are rare. Michael and co-workers (Friedman et al. 2001) studied the impact on air quality and childhood asthma of changes in transportation and commuting behaviors during the 1996 summer Olympic games in Atlanta, and came to the conclusion that efforts to reduce downtown traffic congestion in Atlanta during the Olympic Games resulted in lower rates of childhood asthma events.

To fulfill its commitment to a successful 2008 Olympic and Paralympic Games, the Chinese government made unprecedented efforts to improve the air quality in Beijing, one of world's most polluted cities. Between 1 July and 20 September 2008, temporary vehicle restrictions were implemented: "yellow-labeled" trucks (trucks that failed emission standards) were banned, and Beijing-registered vehicles were allowed on roads every other day. Beginning on 8 August, the opening day of the Games, strict restrictions on polluting industries were imposed in Beijing and surrounding provinces. The 2008 Beijing Olympics provided a unique opportunity to evaluate the public health benefits of air pollution reduction. We report findings on air pollution meteorology and outpatient visits for asthma among adults in Beijing during the 2008 Summer Olympic Games.

In this study, we focus on the impact of weather conditions on air quality and health effects. It is well known that meteorological factors affect ambient air pollution in numerous ways. Emission rates of air pollutants may be related to meteorological conditions directly, e.g., evaporative emission, or indirectly, e.g., increases in energy demands for space heating in cold seasons (Sochez-Ccoyllo et al. 2006; Zhang et al. 2005b). However, the most important role of meteorology is in the dispersion, transformation and removal of air pollutants from the atmosphere. Numerous meteorological variables, often interrelated, can affect ambient air pollution levels. Studies of the relationship between air pollution and individual meteorological variables may be misleading as they do not account for the interrelation between variables, while air pollutant levels normally respond to all meteorological variables representing an air mass.

The Plam (parameter linking air quality and meteorology) index was used to evaluate air pollution meteorological conditions. The Plam index was derived from relationship of particulate matter with aerodynamic diameter less than 10 μm (PM_{10}) and key meteorological data on the basis of summer data (from July to September) during 2000–2007 in Beijing and its surrounding areas. The meteorological data include air temperature, relative humidity, winds, air

pressure, visibility, clouds, evaporation, air stability and weather phenomena. "Bad" air quality days with higher Plam values and higher PM_{10} are always found associated with high temperature, high humidity, lower wind speed and high stability. A high Plam index at Beijing indicates the high degree of stable weather in Beijing. Also, high Plam index values at sites in areas surrounding Beijing show that weather conditions there will be more favorable for transporting pollutants to Beijing. Thus, the Plam index represents one main sensitive dependent of air pollution impact, i.e., the combination of meteorological factors and air pollutants.

The functional form of Plam (Yang et al. 2009; Zhang et al. 2009; Wang and Yang 2000; Yang and Wang 2005; Zhang et al. 2005a) is expressed as:

$$\text{Plam} \propto \beta f_c \theta_e / (T \cdot C_p) \cdot V_\Omega$$

Where β is a constant that depends on season, local topography and emission sources; in this study it is correlated with PM_{10} concentration. θ_e is wet-equivalent potential temperature and can be calculated by:

$$\theta_e = \theta \exp\left(\frac{L_w}{C_p T}\right)$$

θ is potential temperature, T is the temperature, C_p is the heat capacity of air, and L_w is the latent heat for condensation or evaporation of water vapor. f_c is a condensation function; its physical interpretation for concentration of pollutants is: precipitation would not occur if f_c is below a critical value. In this case f_c makes a positive contribution to Plam index, and this is often correlated to light fog or haze. f_c is described as:

$$f_c = \frac{f_{cd}}{\left(1 + \frac{L}{C_p} \frac{\partial q_s}{\partial T}\right) \cdot p},$$

where p is air pressure, q_s is saturated vapor pressure and f_{cd} is dry condensation function (only related to air temperature).

Finally, V_Ω is the projection to Beijing from surrounding areas, representing the possibility that pollution is transported to Beijing. All sites surrounding Beijing were considered, and V_Ω was calculated according to the wind direction of these sites with respect to Beijing, as well as wind speed. That is, V_Ω was used to predict the weather conditions to determine if they were favorable for transporting pollutants from these areas to Beijing. V_Ω is expressed as follows:

$$V_\Omega = \frac{(1 - \mu)^{i-1}}{\mu}$$

Where i is a natural number ($1, 2, \dots, \infty$) representing levels: the smaller the number i is, the greater the fit to V_{Ω} and the greater the impacts on the target (Beijing area). $\mu \in (0, 1)$ is the experiment number.

According to recent studies, inhalable particulate matter and ozone are the atmospheric conditions most correlated to asthma. Considering the difference in their atmospheric activities, PM_{10} was combined with meteorological factors in the Plam index in an attempt to define a correlation. More details on the Plam index can be found in the study of Zhang et al. (2009). Regarding ozone, cumulative effects were studied in addition to single day effects.

Methods

Study design

Three study periods were defined: baseline period (1–30 June: before any air pollution controls), pre-Olympics (1 July–7 August: transportation restrictions in effect), and Olympics (8 August–20 September: further restrictions on industrial emissions). Daily air pollution data, including PM_{10} , aerodynamic diameter less than $2.5 \mu m$ ($PM_{2.5}$), ozone (O_3), sulfur

dioxide, nitrogen dioxide and carbon monoxide, were obtained from three monitoring stations in urban Beijing (Fig. 1), and the average values across stations were used. The Plam index was calculated each day according to the PM_{10} concentration and meteorological data.

Medical definitions and data collection

Data on outpatient visits for asthma were obtained from the database of the asthma registry of the Institute of Respiratory Medicine, Beijing Chaoyang Hospital. We chose the asthma registry as our study base population, and daily data on outpatient asthma visits were obtained from this registry; visitors to Beijing were excluded. This registry began in 2006 and patients were followed up regularly. It covers adult residents (mean age: 51.1 years) of urban areas of Beijing and had 1,475 asthma patients by August 2008.

Air quality data collection

Reactive gas monitoring

Commercial instruments from Thermo Environmental Instruments (Franklin, MA) were used to continuously measure O_3

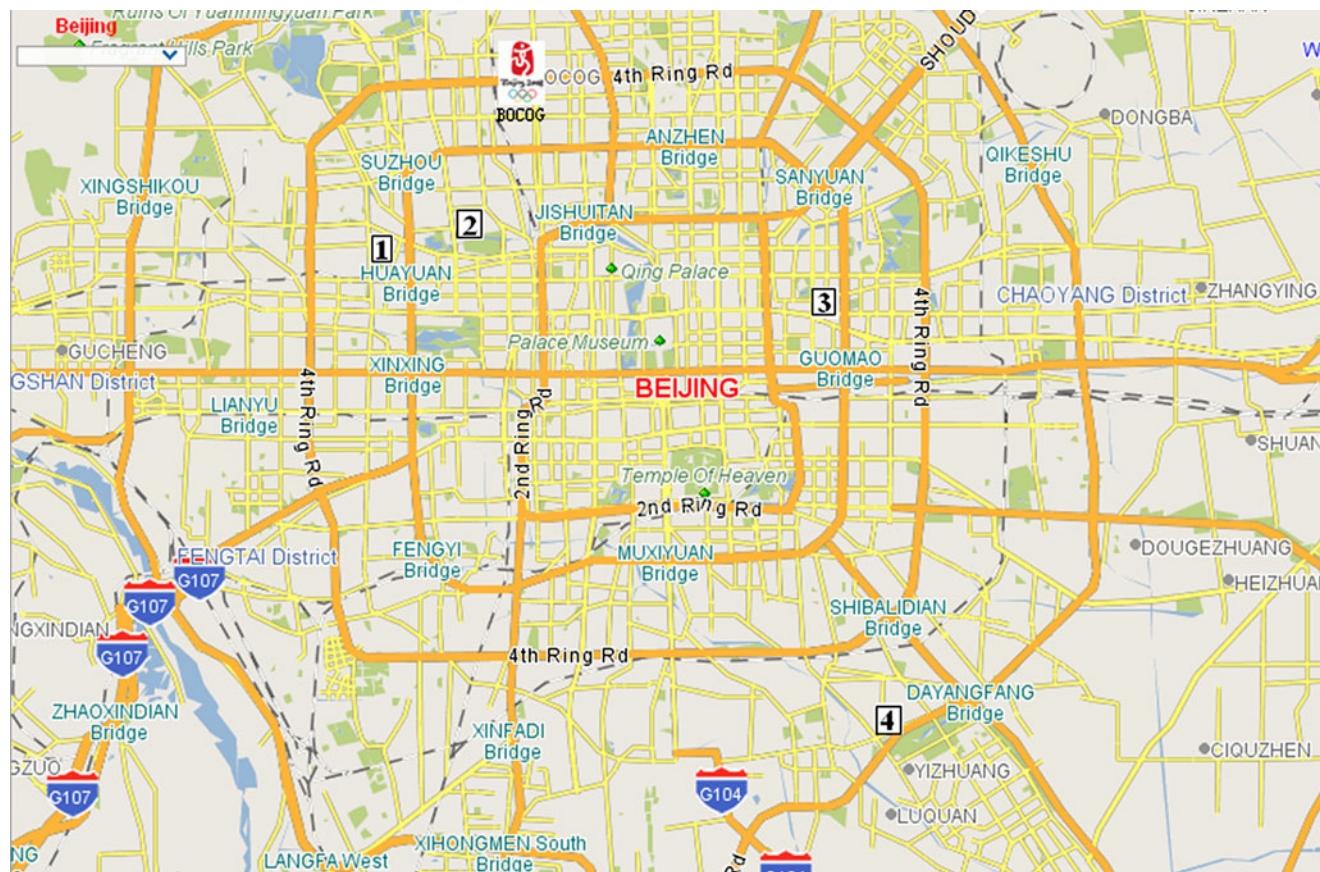


Fig. 1 Sites used in this study: 1, 2, 4 stations monitoring air pollutants; 3 Beijing Chaoyang Hospital

(TE 49C), NO/NO₂/NO_x (TE 42CTL), CO (TE 48C), and SO₂ (TE 43CTL). All instruments were housed in an air-conditioned room. A Teflon inlet tube, 1.8 m above the roof of the building, was shared by the analyzers. Daily zero/span checks and multipoint calibrations were done using a dynamic gas calibrator (TE 146C) in combination with a zero air supply (TE 111) and a set of standard reference gas mixtures (National Institute of Metrology, Beijing, China). Measurement signals were acquired every 6 s and recorded as 5-min averages. For ozone, the standards are traceable to the Standard Reference Photometer (SRP) maintained by WMO World Calibration Centre in Switzerland (EMPA). The national reference gases of SO₂, NO, and CO are compared against NIST-traceable standards from Scott Specialty Gases (Plumsteadville, PA). After correction of data on the basis of multipoint calibration, hourly average data were calculated and used for further analysis. More details of the instrumentation and data process in observations can be found in Lin et al. (2008) and Xu et al. (2008).

The ozone concentration chosen to represent each day's exposure was the peak 1-h ozone concentrations and the mean value from 1000–1800 hours in the day.

Particulate matter

Tapered element oscillating microbalances (TEOM, model 1400a, Rupprecht and Patashnick; Thermo Electron, East Greenbush, NY) operated at a controlled flow rate of 4 L/min were used to record continuously the PM₁₀ mass concentrations averaged over 5 min periods. PM_{2.5} mass concentrations were recorded by another TEOM with a PM_{2.5} impactor installed in the inlet of the monitor.

Statistical analysis

All collected data was analyzed to determine the percentage change in mean values during the Olympic period compared with the 2008 summertime baseline period. One-way analysis of variance *t* test was used to determine if the daily air pollutant, meteorological factor, and Plam index values differed significantly between the three study periods. Significance was defined as $P < 0.05$.

We used time-series Poisson regression models to estimate the relative risk (RR) for asthma outpatient visits associated with pollution levels. We used generalized estimating equations (GEE) with AR(1) to address possible serial correlation in the number of asthma events. Models were implemented using the Zelig Package in R (Lam 2007). Covariates included day of the week, mean temperature (lagged 1 day to improve the fit of the model) and humidity on the same day. Seasonality and time trends were not included due to the short observational period. To estimate the changes in asthma visits associated directly with air quality controls

during Olympic Games, we modeled the pre-Olympic and Olympic periods. Four-week baseline periods were used to avoid the spring season, which can affect ozone levels and exacerbate asthma rates.

In addition to our analyses comparing the Olympic period with the baseline period, data for all 79 study days were used to examine the relationship between ozone accumulation and daily asthma events. The mean number of asthma events was determined for days in which the peak ozone concentrations for that day plus the previous 2 days averaged less than 70 ppb (low cumulative exposure), 70–100 ppb (moderate cumulative exposure), or 100 ppb or more (high cumulative exposure). Controlling for day of the week and minimum temperature (lagged 1 day) in a Poisson regression model, the RR of asthma events was determined at cumulative ozone concentrations of 70–100 ppb, and 100 ppb or more compared with ozone concentrations less than 70 ppb.

Results

Figure 2 shows the good level of agreement between the Plam index, PM, and air pollution index ((API; taken from Beijing Municipal Environmental Protection Bureau, <http://www.bjepb.gov.cn/bjhb/tabid/69/MoreModuleID/445/MoreTabID/66/Default.aspx>), suggesting that the Plam index was an effective indicator of air quality.

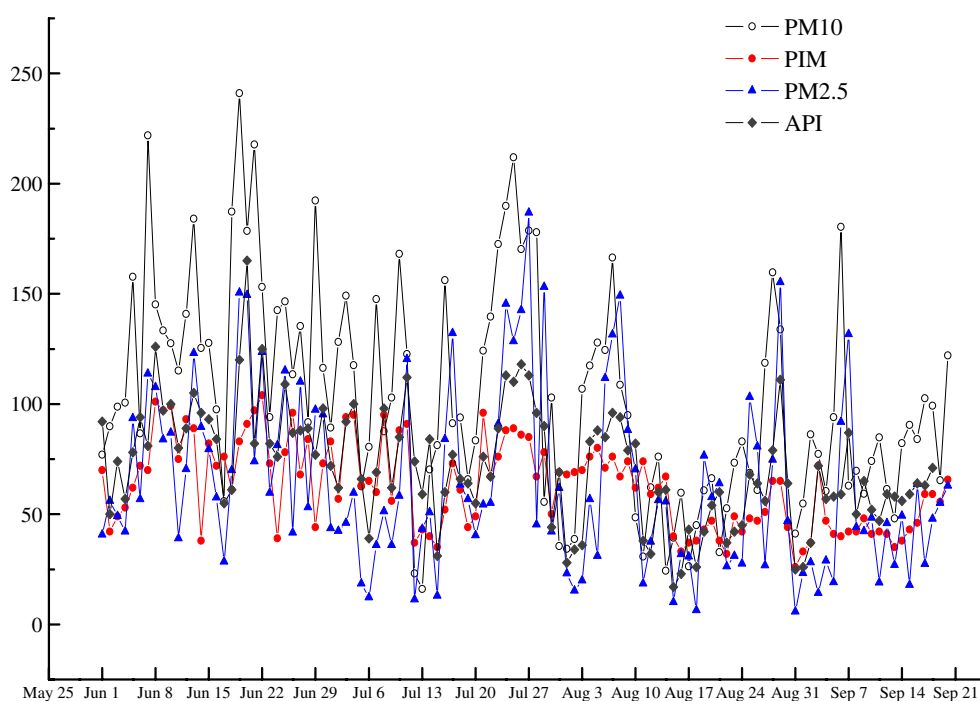
Figure 3 shows the change in air pollutants before and during the Olympic Games. Compared to the baseline period, NO, NO_x, SO₂, O₃ (mean value of 1000–1800 hours), PM₁₀ and PM_{2.5} dropped about 61.8%, 13.1%, 36.9%, 12.6%, 45% and 41%, respectively. More details can be seen in the study of Zhang et al. (2009).

We conclude that the measures in Beijing during the Olympic Games reduced ozone and other air pollutants and were associated with a significant, albeit temporary, decrease in the burden of asthma among Beijing's adults. Our study suggests that, even in a heavily polluted city, air pollution control measures are able to lower air pollution levels and, consequently, lower asthma morbidity in local residents. More effective measures for control of ozone pollution are needed in large Chinese cities.

A total of 937 asthma visits were reported, among which 249, 461 and 227 were during the baseline, pre-Olympic and Olympic periods, respectively. The PM_{2.5} concentration was substantially lower during the Olympic Games than in previous periods (Table 1), while O₃ levels decreased slightly. Interestingly, compared with baseline, the O₃ level was 13.3% higher in the pre-Olympic period. Changes in temperature and humidity between baseline and Olympic Games were not statistically significant.

The average numbers of outpatient visit for asthma were 12.5 per day at baseline and 7.3 per day during the Olympics—

Fig. 2 Time-series values of the pollution linking meteorological (Plam) index, PM_{10} , $PM_{2.5}$ and air pollution index (API) before and during the Olympic Games



a 41.6% overall decrease (Table 1). Compared with baseline, the Games were associated with a significant reduction in asthma visits (RR 0.58, 95%CI: 0.52–0.65). Asthma visits were also significantly higher at 16.5 visits per day during the pre-Olympic period (RR 1.32, 95% CI: 1.15–1.52).

We used data from the entire 79-day study period to analyze the relationship between the number of asthma events on a given day and the average daily average (1000–1800 hours) ozone concentration during the preceding 48–72 h. The results showed that the RR of asthma events

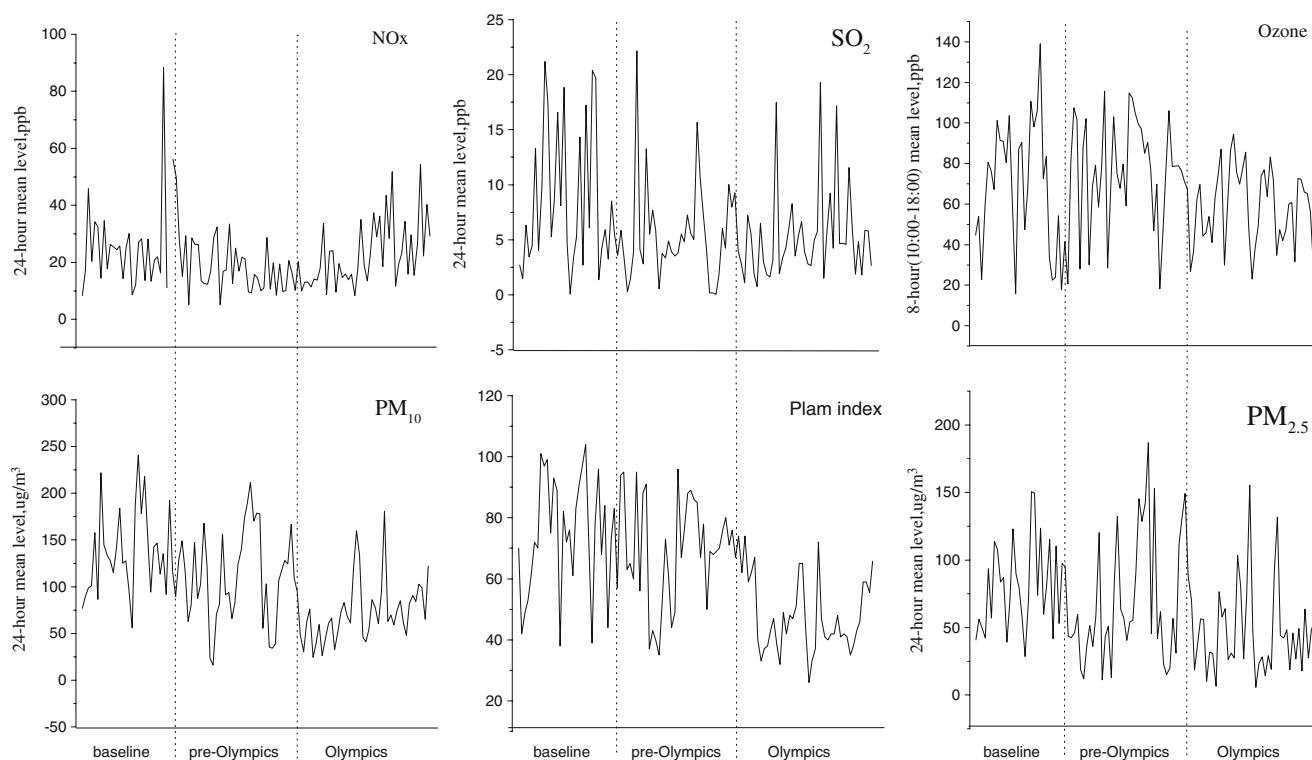


Fig. 3 Mean levels of major pollutants and the Plam index before and during the 2008 Olympic Games [Ozone (max): max-value of ozone during the day]

Table 1 The relationship between air quality measures and adult outpatient visits for asthma before and during the 2008 Summer Olympic Games in Beijing. Data are presented as mean values unless otherwise noted. *PM2.5* Particulate matter with aerodynamic diameterless than 2.5 μm , *PM10* particulate matter with aerodynamic diameter less than 10 μm , *O3* ozone, *RR* relative risk, *CI* confidence interval, *Plam* pollution linking meteorological index

Period ^a	Asthma events (/day)	Plam	PM2.5 ($\mu\text{g}/\text{m}^3$)	PM10 ($\mu\text{g}/\text{m}^3$)	O3 (ppb)	Temperature ($^{\circ}\text{C}$)	Humidity (%)	Relative risk of outpatient visit for asthma	
								Univariate RR (95% CI)	Adjusted RR (95% CI) ^c
Baseline	12.5	74.4	78.8	136.1	65.8	22.8	68.5	1.00 (Ref.)	1.00 (Ref.)
Pre-olympic period	16.5*	69.5	72.3	110.1*	74.6	27.1	7.27**	1.32 (1.15–1.52)**	1.24 (0.93–1.76)
Olympic period	7.3*	49.2**	46.7**	74.3**	61	23.8	69.6	0.58 (0.52–0.65)**	0.50 (0.47–0.55)**

* $P < 0.05$ (two-sided), ** $P < 0.01$ (two-sided)^a Baseline period: 1–30 June 2008, no air cleaning measures; pre-Olympic period: 1 July– 7 August 2008, transportation restrictions in effect; Olympic period: 8 August–20 September, 2008, further restriction on industrial emission^b Adjusted for day of the week, temperature and humidity

increased stepwise at cumulative ozone concentrations 70–100 ppb and 100 ppb or more compared with ozone concentrations of less than 70 ppb (Table 2). This trend was significant. A 3-day cumulative exposure measure was selected for the analysis shown in Table 2 instead of a single-day or 2-day exposure measure because it was found to be more consistently correlated with asthma events (Table 3). These data suggest that the cumulative effect of moderate levels of ozone and other pollutants during a more extended period is as, or more, important to respiratory health than single-day levels.

Discussion

Evidence linking air quality to respiratory health has been accumulating in recent years (Forsberg et al. 1998; Ko et al. 2007). Many studies have demonstrated significant associations between days with high ozone levels and increased rates of asthma exacerbations (McDonnell et al. 1999; McDonnell et al. 2002; Salam et al. 2009). Our results support these previous findings and also indicate that extended reductions in ozone and inhalable particulate matters would decrease the relative risk of asthma events. The results of our study were similar to those of Michael

and co-workers (Friedman et al. 2001) during the 1996 Summer Olympic Games in Atlanta, though the concentrations of pollutants and RR of single pollutant were different.

Moreover, analysis of meteorological factors was emphasized in our study. Several studies have shown that meteorological conditions affect urban air quality trends, temperature and mixing height, strongly influencing ozone conditions (Elminir 2005; Wise and Comrie 2005; Sochez-Ccoyllo et al. 2006), while moisture levels (particularly relative humidity) are the strongest predictors of PM concentrations (Rigby and Toumi 2008). As a result, meteorological conditions affect human exposure to air pollution (Leitte et al. 2009). Meteorological variability typically accounts for 40–70% of ozone variability and 20–50% of PM variability (Lu and Chang 2005; Wise and Comrie 2005; Sui Ke ke et al. 2007). According to most studies, the two air pollutants of most concern for asthma are surface ozone and particulate matter. Thus, it is reasonable to consider more meteorological data while studying the relationship between air pollution and health effects. Kassomenos et al. (2008) has shown that artificial neural networks in combination with dispersion and meteorological models can be used as predictive models to identify days of high risk for public health.

Table 2 Relationship between asthma events and the 3-day cumulative ozone levels during the 79-day summer study period. Relative risk (RR) based on Position model (fraction of total acute care events with a primary diagnosis of asthma); time-series regression analysis wasadjusted for day of the week (weekday vs weekend) and minimum daily temperature (lagged 1 day to minimize serial correlation). *CI* Confidence interval

Ozone < 70 ppb		Ozone 70–100 ppb		Ozone $\geq$ 100 ppb	
Mean daily asthma events	RR	Mean daily asthma events	RR (95% CI)	Mean daily asthma events	RR (95% CI)
8.3	1.00 (ref.)	11.6	1.34 (1.15–1.56)*	16	1.79 (1.53–2.08)*

* $P < 0.01$

Table 3 Comparison of the relative risk of asthma events per 50-ppb incremental change in ozone and 10- $\mu\text{g}/\text{m}^3$ incremental change in PM₁₀ levels based on a same-day, 2-day and 3-day cumulative exposure measure. PM₁₀ indicates particulate matter of 10 μm or smaller; same day, single-day measure of exposure (day of asthma event only); 2-day,

2-day measure of exposure (day of asthma event plus the preceding day); and 3-day measure of exposure (day of asthma event plus the preceding 2 days). Relative risk based on Poisson time-series regression analysis was adjusted for day of the week (weekday vs weekend) and minimum daily temperature (lagged 1 day to minimize serial correlation)

Ozone			PM ₁₀		
Same day	2 day	3 day	Same day	2 day	3 day
1.26 (1.03–1.55)*	1.27 (1.16–1.39)*	1.29 (1.17–1.42)**	1.03 (1.01–1.06)	1.02 (0.99–1.05)	1.01 (0.99–1.02)

* $P < 0.01$

In our study, other than controlling for temperature and relative humidity, the Plam index was introduced to express meteorological pollution conditions. The Plam index emphasizes the impact of meteorological factors on air pollution. According to the data on PM₁₀ concentrations from nine urban stations in Beijing (Sui Ke ke et al. 2007), PM₁₀ pollution at each station differed very obviously before 2003; however, since multiple measures were taken in 2003, PM₁₀ pollution in each station has become consistent, becoming isochronous in 2006. This phenomenon indicated the effect of the controlling measures, the decrease in man-caused pollution, and the transformation from local to regional levels of air pollution. Thus, pollution status would be influenced primarily by meteorological conditions, and it makes sense to include meteorological factors in evaluating human exposure.

As an attempt to do this, in our study Plam index combined with PM₁₀ was used to assess human exposure to pollution and meteorological conditions. Compared with PM₁₀, the lag-1-day Plam index brought more information: the lag-1-day PM₁₀ showed no significant effect on asthma morbidity, which was in accordance with many studies; however, the Plam index showed significant correlation with asthma events. Future studies may combine other pollutants with meteorological factors as well.

It can be seen from Table 1 that, compared with baseline period, the ozone concentration in the pre-Olympic period was higher, while the Plam index did not decrease significantly; the relative risk of asthma morbidity was significantly higher. Therefore, stronger controlling measures for ozone should be taken in future.

We found variation in the relative change in asthma events during the Olympic Games. Of the factors potentially affecting asthma morbidity that we could readily assess, meteorological pollution conditions and air quality remain the likely cause for the decline in asthma acute care events. Our analysis demonstrated that a large and significant decrease in pollution meteorological conditions, ozone concentrations, and to a lesser extent, PM₁₀, PM_{2.5}, could decrease the risk of asthma morbidity.

This study clearly demonstrated the impact of meteorological conditions on air pollution. PM₁₀ and PM_{2.5} concen-

trations recorded a drop of about 45% and 41% in the Olympic period compared with those in baseline period. Though two control measures were taken in July, PM₁₀ and PM_{2.5} concentrations in the pre-Olympic Games period were not significantly decreased compared with the baseline period. Looking at the meteorological conditions, after 20 July, there was a period of unfavorable weather conditions between 24 and 28 July and 5–8 August that led to more aerosol formed in the atmosphere, which showed that, at a time when emissions changed little, weather conditions played a greater role in the formation of atmospheric aerosols over Beijing and its surrounding areas during the summertime.

We observed unique weather patterns from 8 August to 17 September 2008 that were favorable for good air quality:

In 8–9 August 2008, the first 2 days of the Olympic Game period, Beijing witnessed a stable weather conditions under the combined influences of the eastward shifting continental transformed high and subtropical high, which were not conducive to the dispersal of air pollutants. During 10–24 August, the subtropical high retreated southeastwards dramatically, and Beijing was mainly under a frequent eastward-shifting westerly trough and cold continental high, hence clear to cloudy weather or showy showery weather prevailed over Beijing, associated with more northerly winds, which was favorable for clean weather, particularly when the pollution-control measures were in place simultaneously. The good air quality conditions included the effects of wet deposition atmospheric compositions and a clearer influence of cloudy days upon ozone formation. The Plam values also clearly indicate the direct and detrimental contribution of weather conditions to air pollution in Beijing. No doubt, the unique weather conditions in Beijing during the Olympic were very favorable for good air quality.

The stable weather conditions over the Beijing area as defined refer to a less changeable upper-air circulation pattern, with the ground being controlled by weak air pressure field, without any significant cold air invasion. More specifically, the wind was weak (velocity less than 3 m/s, with corresponding wind force below Force 2 on the Beaufort Wind Scale), with the lower atmospheric layer

being stable without any evident precipitation, and visibility being lower (usually less than 10 km).

To assess the effectiveness of pollution control measures by removing the effects of weather conditions as far as possible, we studied some periods from June to September 2008 that had comparable stable weather conditions.

Meteorological conditions in 19–22 June and 25–30 June were characterized with a stable weather pattern, similar to those in 28–29 August and 6–7 September. Plam index, PM₁₀ concentration and asthma events were significantly lower in the latter two periods than in the former two, while ozone and PM_{2.5} concentrations were not significantly changed. Thus, we can also examine the effectiveness of the emission situation after the Olympics by removing the effects of weather conditions as much as possible.

Ozone concentrations in the Olympic Period were not significantly lower than in the baseline period. The weather conditions, more northerly wind and more cloudy and raining days, were not favorable to greater O₃ formation, although the emission conditions were suitable.

Our study methods and findings have several limitations. The special nature of the Olympic Games, the relatively short intervention period and limited statistical power, and the limited number of air pollution monitoring sites and medical data make firm conclusions difficult. Unmeasured medical or social factors may have influenced our findings. However, the power of the Olympic Games to transform behavioral norms should not be underestimated and deserves close scrutiny for its lessons.

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