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PM_{10}, Ambient Temperature and Relative Humidity during the XXIX Summer Olympic Games in Beijing: Were the Athletes at Risk?

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ABSTRACT

Research into exercise and particulate air quality demonstrated that increased physical activity and the related increase in minute ventilation are decisive factors enhancing the effect of polluted air on the well-being and/or health of the examined individuals. As the intensity of exposure increases, so does the amount of inhaled particulate matter. These facts were among the main subjects of heated discussions during the preparatory phase of the XXIX Summer Olympic Games, held in August 2008 in Beijing, China, because this megalopolis is one of the most polluted urban areas in the world. To assess the effect of air pollution on the elite athletes health, ambient temperature, relative humidity and particulate matter with aerodynamic diameter below 10 µm (PM_{10}) were measured during the XXIX Olympic Games in Beijing between August 3 and 24, 2009 in the Beijing Olympic Village. Continuous (15-minute) temperature and relative humidity values were monitored by a datalogging thermo-hygrometer, and PM_{10} measurements were performed by a fast-responding DustTrak nephelometer. The temperature and PM_{10} concentrations were significantly higher during the week preceding the Olympic Games than during the Games. In contrast, the relative humidity was lower during the pre-Games period than during the Games. One possible explanation for this fact is that the promised restrictions of emissions in the traffic and industrial sector may have been successful; at the same time, however, decreased ambient temperature and increased frequency of rain presumably contributed to the substantial improvements in weather and pollution conditions. According to our results, we can conclude that the participants at the XXIX Summer Olympic Games in Beijing were not at risk from poor air quality in terms of health and/or performance.

***Keywords*:** Olympic Games; Air pollution; Particulate matter; Exercise; Sport.

INTRODUCTION

Research into exercise and particulate air quality demonstrated that increased physical activity and the related increase in minute ventilation are decisive factors enhancing the effect of polluted air on the well-being and/or health of the examined individuals. As the intensity of exposure increases, so does the amount of inhaled particulate matter (Carlisle and Sharp, 2001; Daigle *et al.*, 2003; Mittleman, 2007; Thompson *et al.*, 2007; Rundel and Caviston, 2008). Exercise at high ambient aerosol levels may increase the risk of lung and vascular damage, not only because total particle deposition increases in proportion to minute ventilation, but also because the deposition fraction nearly doubles from rest to intense exercise (Daigle *et al.*, 2003; Chalupa *et al.*, 2004).

It has been repeatedly documented that increased concentrations of atmospheric pollutants, together with or independent of high ambient temperature and high relative humidity, may also significantly affect the performance of elite athletes and their health, especially those who suffer from asthma. Pollutants can trigger and exacerbate symptoms, affect airways and increase the risk of exercise-induced bronchospasms (Pierson *et al.*, 1986; Pierson, 1989; Atkinson, 1996; Coris *et al.*, 2004; Seto *et al.*, 2005; McKenzie and Boulet, 2008).

These facts were among the main subjects of heated discussions during the preparatory phase of the XXIX Summer Olympic Games, held in August 2008 in Beijing, China, because this megalopolis is one of the most polluted urban areas in the world (Chan *et al.*, 2005; Huang *et al.*, 2006; Li *et al.*, 2007; Zhang *et al.*, 2007; Chan and Yao, 2008; Wang *et al.*, 2008a; Xu *et al.*, 2008) similarly as other urban and industrial areas in China (Yang *et al.*, 2008; Li *et al.*, 2009; Shen *et al.*, 2009). Before the games began, air pollution and its potential

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adverse effect on the athletes' health and performance was one of the main topics for the media all over the world (e.g. Bagenal, 2008; Shipley, 2008; Watts, 2008). At the same time, a number of scientific papers tried to predict the impact of pollution on the performance of elite athletes participating in the games (Brajer and Mead, 2003; Streets *et al.*, 2007; Borresen, 2008; Lippi *et al.*, 2008; McKenzie and Boulet, 2008; Mead and Brajer, 2008; Salthammer, 2008).

Because of these predictions, the main aim of our monitoring was to provide the Czech Olympic support team with relevant information which could be used to adjust the daily regime of athletes according to the expected unfavourable environmental conditions. At the same, these on-site PM_{10}, temperature and relative humidity measurements before and during the games allowed us to assess whether restrictions on urban traffic and limitations imposed on industrial production by the Beijing municipal administration resulted in noticeable improvements in air quality during the Olympic event.

For the purpose of this study, we have divided the monitoring period into two parts: a "pre-game period" and the period of the Olympic event, hypothesizing that the measures promised/taken by the Beijing municipal and Chinese national governments (restrictions on urban traffic as well as limitations imposed on industrial production in the vicinity of the city – for details see UNEP, 2009; Wang *et al.*, 2009b) would result in apparent improvements in air quality during the games. The results of our measurements are presented below.

METHODS

A new fast-responding, factory-calibrated, real-time DustTrak laser photometer (TSI, Model 8520), suitable for determination of aerosol mass concentrations between 0.001 and 100 mg/m^3 for particles ranging in size from 0.1 to 10 μm, was used to measure the PM_{10} concentrations. Logging interval of the photometer was set at 15 minutes. Zero and air-flow checks were performed before and after the measurement campaign and once during the measurements. Neither zero nor air-flow drift were observed. The instrument was placed in the Olympic Village in Beijing in the 1st floor on a balcony on the North side of the B3 Tower building.

The ambient temperature and relative humidity were recorded together with the PM_{10} data by a Commeter D3121 combined thermo-hygrometer. The logging interval of the temperature/relative humidity monitor was also set at 15 minutes. The measurements were begun in Beijing on August 3 and terminated on August 24, 2008. The whole monitoring period was divided into two parts: the "pre-game" time between August 3 and 8 and the "during games" time between August 9 and 24, 2008.

Because of the known bias of the photometer, the raw data retrieved from the photometer were treated in two ways. First, according to the user's manual, the instrument provides realistic data when operated below 95% relative humidity. Therefore, we removed all 15-minute PM_{10} values recorded during these high relative humidity episodes from the data set and compared it with the uncensored data set before the final analysis. The statistically proven difference between the two data sets would mean that only censored data will be used for further calculations and those recorded in periods with over 95% relative humidity will be discarded. Since no statistical difference was obtained between the censored and uncensored data sets (Fig. 1), we used all the photometer data for the assessment.

The second treatment was aimed at correcting the overestimation known for light scattering aerosol monitors. According to the scientific literature, the DustTrak photometer over-reports real aerosol concentrations by a factor of two to three compared to the reference methods (Chung *et al.*, 2001; Yanoski *et al.*, 2002; Ramachandran *et al.*, 2003; He *et al.*, 2004; Jenkins *et al.*, 2004; Branis, 2006). Thus, we divided all the raw (15-minute) photometer data by an arbitrary coefficient of 2.5 and used the corrected data for the 24-hour average calculation. The corrected data were used in discussion of the reliability of our nephelometer measurements.

Because only one-spot measurements from the Olympic village were performed in our study, to overcome this problem we compared our non-corrected light scattering data with the outcomes of four independent measurements (two of which were performed with the same instrument) taken in different places before and during the Olympic Games. The first comparison was made between our data and results presented in the independent environmental assessment of the 2008 Beijing Olympic Games (UNEP,

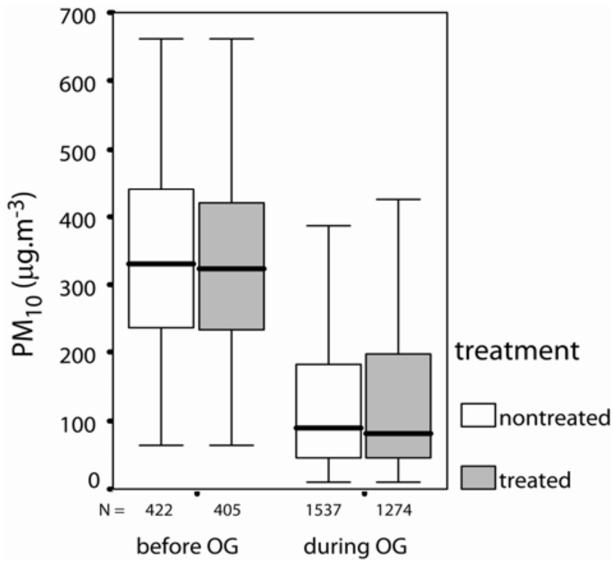

Fig. 1. Boxplot of 15-minute non-corrected PM_{10} concentrations during the pre-games period (before OG) and during the Olympic Games (during OG). The median, 50th and 75th percentiles are given in the box plot. Whiskers show the maximum and minimum values (outliers and extremes are not shown). Non-treated data = all PM 15-min readings included; Treated data = PM readings recorded at relative humidity over 95% discarded.

2009). The UNEP PM_{10} air quality data were based on the average of 27 monitoring sites of the National air quality network operating in Beijing during the games. The daily averages between August 3 and 24, 2008 (22 days) were compared in this analysis. For the second comparison we used high volume cascade impactor PM_{10} measurements recorded on the roof of the Peking University Geology Building (situated approx. 6 km from our place of measurement) during the Olympic Games, recently published by Wang *et al.* (2009a). Also for this comparison the 24-hour data between 3 and 24 August 2008 (22 days) were available. The third data source was the PM_{10} DustTrak dataset published by the British Broadcasting Corporation on the Internet before and during the Olympiad (BBC, 2008). Altogether 22 days between August 3 and 24, 2008 were available for the analysis. The fourth comparison was made with data presented on a poster (Wang *et al.*, 2008b) during the 2008 AAAR conference (the electronic version of the poster copy was kindly provided by the authors). In this case the 24-hour $PM_{2.5}$ concentrations recorded by the same type of monitor (DustTrak) between 3 and 20 August 2008 (18 days) were used for comparison. The measurements were taken about 3.5 km from our monitoring location on the premises of the Peking University Health Science Center campus.

Since we had no access to the original numerical data of the above mentioned studies, we manually reconstructed the values from the graphs available on the Internet (BBC, 2008) or from printed graphs (UNEP, 2009; Wang *et al.*, 2008b; Wang *et al.*, 2009a) by overlapping their enlarged copies with a fine grid of 5 $\mu g/m^3$ and compared the obtained 24-hour data with our non-corrected ones. The correlation coefficients and the ratio between the same-day concentrations taken by the different methods were calculated and discussed in terms of our data quality.

The SPSS package was used for statistical analysis of the results. Non-parametric tests were employed for assessment of differences between the data sets.

RESULTS

The PM_{10} concentrations were highly variable during the monitoring period (The time series of the PM_{10} concentrations are depicted in Fig. 2 and the descriptive statistics are given in Tab. 1). The average (non-corrected) 15-min concentration of PM_{10} over the whole 22-day long measurement period was 177.7 $\mu g/m^3$. The pre-games period (between August 3 and 8, 2008) was characterized by higher PM concentrations (average 352.9 $\mu g/m^3$ non-corrected data) than the period of the games (between August 9 and 24, 2008) when the average 15-minute PM_{10} concentration was approximately three times lower, reaching 114.7 $\mu g/m^3$ (Fig. 2).

The difference between these two periods was highly statistically significant ($p < 0.001$) according to the Man-Whitney test. The maximum concentrations were recorded before the beginning of the event around 2 A.M. on the 7th of August (661 $\mu g/m^3$) and around 2 AM on the 8th of August (559 $\mu g/m^3$); however, a high maximum was also recorded on the first day (August 9) of the Olympic games period (546 $\mu g/m^3$). From then on, 15-minute concentrations over 250 $\mu g/m^3$ (non-correted data) were exceptional.

Similarly to the PM_{10} concentrations, the relative humidity and ambient temperature also varied during the period of measurements (time series of the two meteorological variables are depicted in Fig. 3, descriptive statistics are given in Table 1). The average pre-games humidity was lower (74.8%) than that recorded during the Olympic Games event (81.0%), presumably due to increased frequency of precipitation. According to the

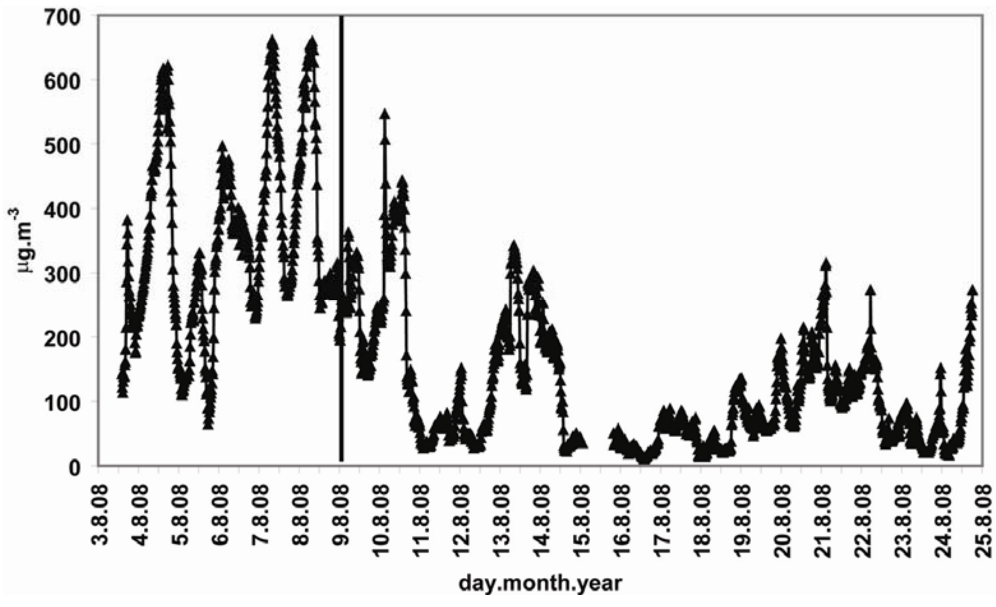

Fig. 2. Time series of 15-min non-corrected PM_{10} concentrations before (3–8 August) and during (9–24 August) the XXIX Summer Olympic Games in Beijing, 2008. The solid vertical line divides the two periods.

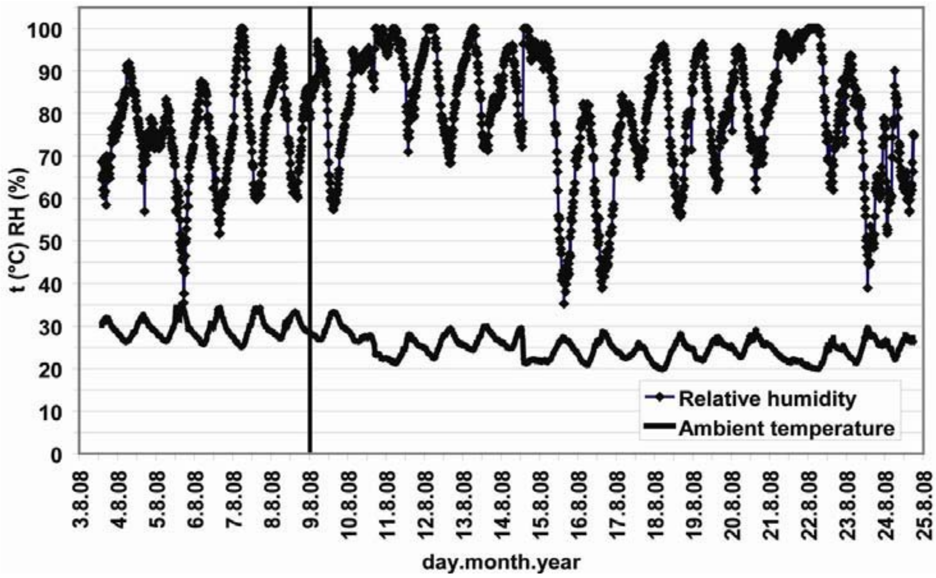

Fig. 3. Time series of 15-minute temperature and relative humidity data before (August 3–7) and during (August 8–24) the XXIX Summer Olympic Games in Beijing, 2008. The solid vertical line divides the two periods.

Table 1. Descriptive statistics of 15-min concentrations of particulate matter (PM_{10}), temperature (°C) and relative humidity (RH) during the Olympiad in Beijing (the original non-corrected DustTrak data are presented for PM_{10}).

	average	SD	median	maximum	minimum
all data (3–24 August)					
PM_{10} (μg/m^3)	177.7	152.1	133.0	661.0	10.0
t (°C)	26.1	3.3	26.1	35.1	19.8
RH (%)	79.4	14.2	80.6	100.0	35.3
pre-games period (3–8 August)					
PM_{10} (μg/m^3)	352.9	146.3	330.0	661.0	64.0
t (°C)	29.6	2.4	29.3	35.1	25.1
RH (%)	74.8	11.5	75.1	100.0	35.5
during games period (9–24 August)					
PM_{10} (μg/m^3)	114.7	93.7	77.0	546.0	10.0
t (°C)	25.0	2.7	25.0	33.3	19.8
RH (%)	81.0	14.6	83.1	100.0	35.3

official reports, there were no rain episodes during the pre-games period (August 3–8, 2008) and 6 days with rain during the Olympic Games (August 9–24, 2008). The variability in the relative humidity during the latter period was much higher than during the pre-games period. The difference between the two values was highly statistically significant ($p < 0.001$) (Fig. 4). On the other hand, the ambient temperature was consistently lower (average 25.0°C) during the Olympic Games event than during the period preceding the games (average 29.6°C). This difference was also highly statistically significant ($p < 0.001$) (see Fig. 4).

Since the DustTrak photometer used for our measurements is known to overestimate the real aerosol concentrations by a factor of about two to three compared to the reference methods, estimates of realistic values for the data recorded during the Beijing monitoring campaign were obtained by dividing the measured values by a coefficient of 2.5.

The results of the treatment (dividing the raw 15-min data by a factor of 2.5) showed that the corrected PM_{10} daily average concentrations before the games (August 3 to 8, 2008) were all above the WHO and EU recommended limits of 50 μg/m^3 (between 88 and 172 μg/m^3), while the concentrations during the Olympic Games event (August 9 to 24, 2008) decreased dramatically to values between 10 and 108 μg/m^3, with most of the daily concentrations being below the limit. Of the 16 days of the sports event, only 5 days exhibited levels higher than the recommended daily limit of 50 μg/m^3 (Fig. 5).

DISCUSSION

There are two basic problems related to the above given results. One of the key factors affecting the data quality is the systematic bias of the instrument used for the PM_{10} measurements; the second one is that data from only a single site were available for the analysis.

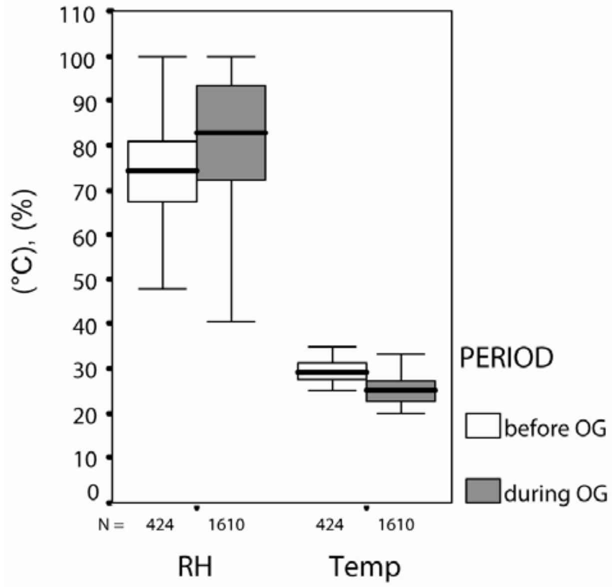

Fig. 4. Boxplot of 15-min data for the ambient temperature (Temp) and relative humidity (RH) before and during the Olympic Games (OG). The median, 50th and 75th percentiles are given in the box plot. Whiskers show the maximum and minimum values (outliers and extremes are not shown).

As stated by Görner *et al.* (1995) nephelometers can be fairly simple and compact instruments with excellent sensitivity and time resolution, however, scattering per unit mass is a strong function of the particle size and refractive index. Therefore, readings from light scattering devices should be calibrated separately for different types of indoor and outdoor microenvironments, as well as for different seasons (Brauer, 1995; Quintana *et al.*, 2000). Researchers who used the same type of instrument suggest that the bias of DustTrak is linearly proportional to the reference methods and that the readings of the instrument can be recalculated according to the ratio between the reference and the photometer readings (Jenkins *et al.*, 2004) or according to a linear regression equation (Chang *et al.*, 2001; Chan *et al.*, 2002ab; Wu *et al.*, 2002; Morawska *et al.*, 2003; Ramachandran *et al.*, 2003; Jenkins *et al.*, 2004; Branis, 2006). Since systematic overestimation between 2–3 fold against the reference values was mentioned in most of the studies using the same type of photometer (Lehocky and Williams, 1996; Ramachandran *et al.*, 2000; Chang *et al.*, 2001; Chung *et al.*, 2001; Moosmüller *et al.*, 2001; Chan *et al.*, 2002ab; Yanoski *et al.*, 2002; Wu *et al.*, 2002; Morawska *et al.*, 2003; Ramachandran *et al.*, 2003; Jenkins *et al.*, 2004), we decided to use a value within this range. In addition, field measurements showed that increased humidity caused an increase in the PM readings (Ramachandran *et al.*, 2003). Quintana *et al.* (2001), who used a different type of photometer (the MIE inc. pDR-1000), also reported elevated mass equivalent readings of the instrument when measurements were taken in high humidity situations (close to a shower, etc.). However, exclusion of the photometer readings recorded by us in Beijing under high relative humidity conditions did not confirm this relationship and justified the use of all the light scattering data in the final analysis. On the basis of the so-far published information on this aspect, we can consider the recalculation coefficient of 2.5 used in the present study to be reliable and conservative.

The second problem in the study was related to the fact that only one-spot measurements were available for the main Olympic Games area air-quality assessment. To overcome this problem, we compared our (non-corrected) data with the outcomes of four independent measurements taken by different institutions and at different places before and during the Olympic Games.

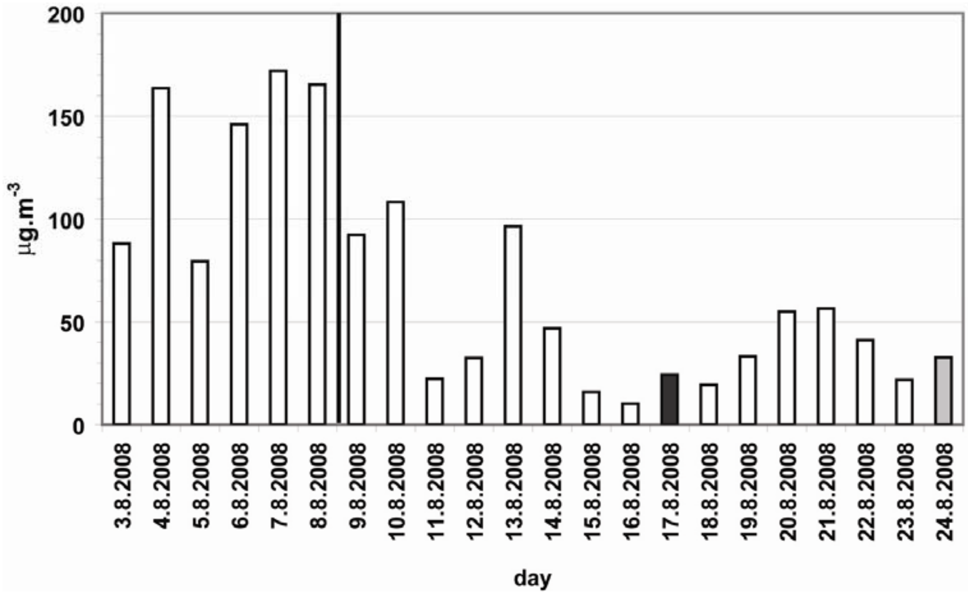

Fig. 5. 24-hour corrected PM_{10} concentrations before and during the Olympic Games. The solid vertical line divides the two periods. The black column indicates the day of women marathon the grey one the day of men marathon.

The comparison with the UNEP (2009) (in fact the Beijing municipal air quality network) results exhibited a very high degree of correlation (0.869). The ratio between our and the UNEP PM_{10} 24-hour data was 2.47 ± 1.22. The association between the two PM_{10} datasets improved (0.945) after eliminating two outliers from the dataset (9.1% of the data), while the ratio remained almost the same (2.35 ± 0.61). Accepting the fact that the UNEP data were obtained from measurements performed by a standard method, the ratio between the two variables showed that the correction factor of about 2.5 is needed to adjust the DustTrak overestimation.

The comparison between the 24-hour high volume cascade impactor PM_{10} (Wang *et al.*, 2009a) and our DT data showed a good correlation too (correlation coefficient 0.884). Also this association improved by discarding two outlying measurements to 0.949. The ratio of our DT and Wang *et al.* (2009a) cascade impactor (1.61 ± 0.89 for full record and 1.51 ± 0.49 after elimination of two outliers) showed that the concentrations measured by the cascade impactor were presumably recorded at a location exposed to higher particulate matter concentrations (close proximity to the Beijing 5th Ring Road) or that lower correction factor would be needed to adjust the DT data.

The third comparison with the Wang *et al.* (2008b) $PM_{2.5}$ daily averaged data measured by the same instrument (DT) revealed also an excellent overlap. The correlation coefficient of 0.934 improved to 0,981 when two outliers were discarded from the dataset. The ratio between our and Wang *et al.* (2008b) concentrations (3.25 ± 1.19 for full record and 3.00 ± 1.00 after eliminating two outliers) indicated that a correction was used to adjust the Wang *et al.* (2008b) $PM_{2.5}$ concentration. This fact was confirmed during discussion with one of the authors who confirmed that to obtain realistic data the readings of their DT were divided by a correction factor of 2.7.

Finally the fourth comparison was made between our and the BBC DT concentrations (BBC, 2008), the only independent measurements which were every day accessible on the Internet several weeks before and during the Beijing Olympic Games. This comparison revealed a very good correlation coefficient of 0.835. After discarding two outliers from the data set (9.1% of the data), the correlation improved to 0.919. The ratio between our and the BBC data for the whole period of measurement (22 days) was 2.14 ± 0.89. Discarding of the two outliers did not substantially change this ratio (2.25 ± 0.86). The ratio between the two datasets revealed that the BBC measurements were either taken at a very clean location, or (most probably) were also adjusted for the photometer bias by a correction factor of approximately two. Unfortunately, no detailed information about the instrument setup, integration time or data treatment could be obtained from the BBC staff performing the measurements. However, in despite of the uncertainties accompanying the BBC measurements, the good accord with our systematic measurements (as well as with the other two ones used in the present study for comparison) suggests that the information provided by the BBC to the general public through the Internet reflected the overall air quality characteristics during the Olympic Games in Beijing very well.

The fact that non-coordinated measurements (taken at different places and/or by different methods in different heights above ground and presumably integrating over different periods of time) performed in the vicinity of the Olympic village exhibited a very high level of accordance allowed us to consider our one-spot measurements from the balcony of the Olympic village as reasonable and representative for the whole area.

The air quality in Beijing has been studied in the past by a number of researchers who concluded that the city is one of the most polluted urban areas in the world (Huang *et al.*, 2006; Li *et al.*, 2007; Zhang *et al.*, 2007; Wang *et al.*, 2008a; Xu *et al.*, 2008). High particulate matter levels were also expected by Olympic officials for the period of the XXIX Summer Olympic Games (Anonymous, 2008). Our data, limited to one-spot photometer measurements, can confirm this fact but only for the pre-game period. Corrected daily DustTrak values (which can be considered to be close to realistic figures) revealed high PM_{10} concentrations over 150 $\mu g/m^3$ during the days prior to the games. Particulate matter levels during the period of the games were significantly lower than expected. The PM_{10} concentrations corrected by a reasonable factor of 2.5 exceeded the WHO and EU recommended limits only in 5 of the 16 days of the competitions.

The sudden drop in particulate air pollution by the beginning of the games can be logically attributed to previously announced drastic cuts in industrial production in the Beijing region and restrictions imposed on urban traffic, namely on the use of private cars (Wang *et al.*, 2008a; UNEP, 2009; Wang *et al.*, 2009b). However, we can document that changes in PM concentrations were not necessarily due solely to restrictions on emission sources. Our temperature and relative humidity data, together with on-site observations, support the concept that a significant part of the pollutants drop was caused by improved weather conditions (cooling of the air, increased frequency of precipitation, windy conditions). Because of this coincidence, it is not clear what proportion of the improvements can be attributed to the mitigation measures and what to favourable weather conditions. Similar uncertainties were mentioned by Cermak and Knutti (2009) in one of the first publications attempting to analyze the effect of emission reduction on improved ambient air quality during the XXIX Summer Olympic Games in Beijing. Also Wang *et al.* (2009a) who also performed a single spot measurements of PM suggested that meteorology accounted for more of the variation (40%) in PM concentration than source control measures (16%). In contrary, Witte *et al.* (2009) who analyzed NO_2, SO_2 and CO satellite data argued that emission control measures had a significant effect on improvements in air quality during the games. Same conclusions were drawn by Wang *et al.* (2009b) who attributed dramatically lower concentrations of black carbon during Olympic Games days to the effectiveness of traffic control regulations.

Results of surface observations and modeling presented by Wang *et al.* (2009c) revealed that the reduction in emissions of ozone precursors associated with the Olympic Games had a signifiant contribution to the observed decrease in O_3 during August 2008, accounting for 80% of the O_3 reduction for the month as a whole and 45% during the Olympics period.

Taking into account the PM_{10} levels recorded by us and by others during the Olympic Games venue, neither the meteorological nor the air quality data revealed any extremes that could be considered hazardous for the participating competitors. We can also conclude that none of the papers aimed at modelling or pre-assessment of pollutant levels during the Beijing games succeeded in their predictions or expectations. Virtually all the predictions speculated that high concentrations of NO_X, O_3 or PM will be reached and concluded that these levels could have negative effects on the athletes' performances and health (Flouris, 2006; Streets *et al.*, 2007; Borresen, 2008; Lippi *et al.*, 2008; McKenzie and Boulet, 2008; Salthammer, 2008). In contrast, our data showed that the PM_{10} concentrations recorded in Beijing could be considered similar to or only slightly higher than those recorded for other cities characterized by high pollution levels, where previous Olympic Games were held (Mexico City, Los Angeles, Athens, etc). According to our results, we can conclude that the participants at the XXIX Summer Olympic Games in Beijing were not at risk from poor air quality in terms of health and/or performance.

Despite the fact that the effect of the announced mitigation strategies and actions taken to improve the environmental conditions during the Beijing Olympic Games cannot be fully assessed and quantified because of the coincidence with favourable weather conditions, the pre-games clean-up activities might have had a substantial side effect in improving the health and living conditions for citizens residing in the Beijing region, as estimated by Brajer and Mead (2003) and Mead and Brajer (2008). As was shown previously for Atlanta, USA (Summer Olympic Games 1996) and Busan, Korea (Summer Asian Games 2002), urban transport control during similar sports events, such as that held last year in Beijing, can significantly improve, not only the performance of elite athletes, but also the status of the health (especially in relation to asthma) of the general population (Friedman *et al.*, 2001; Lee *et al.*, 2007).

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