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Discussions

Traffic restrictions in Beijing during the Sino-African Summit 2006: aerosol size distribution and visibility compared to long-term in situ observations

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Abstract

Based on the long-term in-situ observations of aerosol particle number size distributions and meteorological parameters, the traffic restriction measures during the Sino-African Summit (4–6 November 2006) in Beijing, China have been found to be remarkably efficient in reducing the number concentration of aerosol particles, in particular Aitken and accumulation mode particles, and in improving the visibility. The influence of traffic restriction in Beijing on the particle concentrations differed for different particle sizes. More significant effects on fine particles with diameters ranging from 40 to 800 nm have been found. Based on statistical analysis of long-term observation, under comparable weather conditions, the source strength of the particles in Aitken and accumulation modes seemingly was reduced by 40–60% when the traffic restrictions were in place. It may be mainly due to the reduction of secondary particle formation. Our size-dependent aerosol data also indicate that measures led to reductions in particulate air pollution in the optically most important diameter range, whereas further vehicle control measures may lead to an increase in ultrafine particle formation from the gas phase if the condensational sink further decreased. Assuming that there were no traffic restrictions and with normal levels of the vehicle emissions, the visibilities during the Summit would have been lower by about 50%. The importance of the restrictions is highest when the wind speed is lower than 3 m s^{-1}. The fact that over 95% cases with visual range lower than 5 km during 2004 to 2007 occurred when the local wind speed was lower than 3 m s^{-1} may suggest that future traffic restrictions will lead to significant improvements of visibility in Beijing.

1 Motivation

Particles in the atmospheric arise from natural sources and from anthropogenic activities. They are emitted directly as particles or formed in the atmosphere by gas-to-particle conversion processes. A significant fraction of the tropospheric aerosol is anthropogenic in origin (Seinfeld and Pandis, 1998), in particular at diameters below one micrometer (fine particles) which result from nucleation/condensation of anthropogenic particle precursors or as directly emitted soot particles. Many urban regions face serious particulate pollution problems and their environmental agencies need to understand the most important aerosol sources before implementing clean-air measures.

A forward strategy in trying to understand the relationships between different pollution sources and air quality starts with information on emissions and then predicts the pollution by means of air quality models with different emission scenarios. An inverse research strategy uses the atmosphere as a natural laboratory to estimate the influence of different pollution sources by means of utilizing known changes in certain pollution sources with concurrent measured changes in air quality. Changes in pollution sources may be inadvertent as in the case of the terrorist attacks on 11 September 2001 (Travis et al., 2002) or can be deliberate changes in pollution sources such as in the Heilbronn experiment in June 1994 where during four days traffic restrictions were enacted in search of measurable changes in ozone levels (Moussiopoulos et al., 1997).

Concomitant with its fast economic development, severe aerosol pollution in China has attracted global attention. Beijing, the capital of China, is one of the largest mega cities in the world, with approximately 17 million inhabitants and over 3.1 million motor vehicles to date. Any efforts to improve the air quality of Beijing will require a clear understanding of the potential sources of particles. Traffic emissions are considered to be one of the most important sources of sub-micrometer particles in the urban area of Beijing (Zheng et al., 2005; He et al., 2001; Song et al., 2006; Zhang and Shao, 1997, etc.). Zheng et al. (2005) and Song et al. (2006) indicated that, as a primary source, traffic emissions in Beijing contribute 6–7% to particulate mass concentrations below 2.5 μm ($PM_{2.5}$). The respective contribution from road dust resuspension was estimated to be 7–9%. However, gaseous pollutants are also emitted by vehicular sources, such as NO_x and organic compounds, which are essential for the atmospheric photochemical processes and subsequent gas-to-particle conversion. The latter are closely related to the formation of secondary particulate matter. In total, secondary ammonium, sulfate and nitrate contribute over 35% of $PM_{2.5}$ in Beijing (Zheng et al., 2005;Song et al., 2006). However, this percentage does not include the contribution of secondary organic particles. Zheng et al. (2005) reported that particulate organic matter accounted for over 50% of $PM_{2.5}$ in the urban area of Beijing during winter time, of which less than 30% might be explained by biomass burning (Duan et al., 2004).

As the host of the Olympic Games in summer of 2008, how will Beijing, a city that many people associate with often choking-gridlocked traffic and health-threatening levels of pollution, handle the additional influx of Olympians and their many spectators (Renfrow, 2008)? A specific and mandatory rehearsal of the traffic control strategies, instituted by the Beijing municipal authorities, was conducted in Beijing during 4 to 6 November 2006 in connection with the Summit of the Forum on China-Africa Cooperation (4 and 5 November 2006). News reports on China Daily (2006) suggested that approximately 30% (~800 000) of the cities' 2.8 million vehicles were taken off the roads as a result of measures adopted during the Summit by the Beijing municipal authorities. This rehearsal offers an interesting opportunity to improve our understanding of the complex relationship between emission sources and the concentration level of major atmospheric pollutants in a realistic "natural atmospheric chamber".

Wang et al. (2007) reported that this event was successful with about 40% reduction in associated emissions of NO_x. However, their result was based on satellite remote sensing of columnar atmospheric properties (NO_2 column density) and a 3-dimensional chemical transport model, but lacked in-situ observations, in particular any aerosol data, which are of prime interest with respect to visibility. Also no specific local meteorological parameters were taken into account. In the present study, we analyze the influence of the Summit traffic restrictions on the aerosol size distribution and visibility based on long-term in situ observations as well as meteorological monitoring data in Beijing.

2 Long-term observations of particle number size distributions in Beijing

Since 2004, long-term measurements of aerosol particle number size distributions have been conducted at a site (20 m above the ground level) on the campus of Peking University (PKU site, [39.99° N, 116.31° E]). The campus is located in the northwestern urban area of Beijing, China.

Particles are sampled with a low-flow PM_{10} impactor inlet. Particle number size distributions with electric mobility diameter from three to 800 nm are scanned with a Tandem Differential Mobility Particle Sizer (TDMPS). Design and performances of TDMPS can be found in Birmili et al. (1999). At the same time, an Aerodynamic Particle Sizer (APS, TSI 3321) is used to measure the particle number size distributions with aerodynamic diameters from 800 nm to 10 μm. The relative humidity within the combined system of TDMPS and APS is kept below 30% (Birmili et al., 2004) by adding dryers based on Nafion membrane technology and also silica-gel diffusion-dryers in the aerosol inlet flow and the sheath air flow. The system flow rates have been checked manfully once per week. Aerodynamic diameters measured with the APS have been converted to Stokes diameters by dividing by the square root of a density of dry particles as 1.7 $\mathrm{g\,cm^{-3}}$ (Wehner et al., 2004; Wu et al., 2007; Wu et al., 2008). Corrections considering diffusional and gravitational losses in the sampling system have been applied according to Willeke and Baron (1993). The time resolution of the particle number size distributions, combined with TDMPS and APS data, is 10 min.

A meteorological station has been operated simultaneously to monitor meteorological parameters, including wind speed (*WS*), wind direction (*WD*), relative humidity (*RH*), air temperature (T), and air pressure (P). This station is about 400 m away from the PKU site and is mounted on top of a 20 m high building.

3 Aerosol variability in fine and coarse mode during the summit period

Figure 1 presents the different patterns of size-dependent particle numbers measured at the PKU site in October and November 2006. While the public had been advised to drive less for six days (1 to 6 November 2006), specific and mandatory regulations were instituted only between 4 to 6 November 2006 (Wang et al., 2007). Thus this traffic restrain periods will be referred as “Summit” period in the following text. A notable feature of Fig. 1 is the significant reduction of aerosol particles as a function of particle size in Beijing during 4 to 6 November 2006, compared to the time before and after. These changes coincided with the traffic restrictions instituted during the Summit.

The aerosol exhibited a size-dependent variability during the Summit period. Figure 1 shows that the number concentrations of Aitken mode and accumulation mode particles with diameters from about 50 to 800 nm mostly stayed very low, while this was not the case for the nucleation mode (smaller than 30 nm) and coarse mode (larger than 1000 nm) particles.

There was no obvious influence on the number concentrations of nucleation mode particles (e.g., 11 nm in Fig. 1) by the traffic restriction measure. Instead of decreasing they actually increased in the mornings and early afternoons during the Summit period when the wind speed was higher than 6–8 m s^{-1} (cf. Figs. 1 and 2). Wehner et al. (2004) indicated that new particle formation events in Beijing tended to occur when the total particle surface decreased and the condensational sink was low. Wu et al. (2007) analyzed the new particle formation events at the PKU site during one year. Their results show that when the air mass arrived in Beijing from the north or northwest the formation events generally occur when the local wind speeds are steadily higher than 6–8 m s^{-1} with a condensational sink lower than 0.02 s^{-1}. In Beijing, as in most urban environments, the particle surface concentration is dominated by accumulation mode particles (Wu et al., 2008).

Concurrent with the nucleation mode increase we thus see a sharp reduction in number concentrations of the Aitken and accumulation mode particles (e.g., 53, 108, 693 nm in Fig. 1), coinciding with the traffic restrictions instituted during the Summit. Comparing the fine and coarse mode particles, the major difference was that the reduction of coarse mode particle numbers was not as constant as in the accumulation mode during the Summit. After 5 November, the number concentration of coarse mode particles increased with increasing north/northwest wind (cf. Fig. 1e–f and Fig. 2a–b). The primary particles emitted directly from the vehicles are dominated by the fine particles with diameters below 500 nm and peaking at around 40 to 100 nm (Janhäll et al., 2004; Imhof et al., 2006; Rose et al., 2006; Wehner et al., 1999, 2002; Wehner and Wiedensohler, 2003). Also nucleation/condensation of vehicle emitted particle precursors mostly contribute to the concentration of particles at diameters below one micrometer (fine particles). It may indicate that the traffic restrictions were more effective concerning fine than coarse particles.

In the next section, we will relate this reduction to synoptic, seasonal, and long-term aerosol changes according to the long-term aerosol records in Beijing, which will provide a general statistical quantification of this reduction.

4 Statistical comparisons of summit and non-summit periods

The temporal variability in particle number concentrations reflects a combination of changes in emissions, changes due to variations in meteorological conditions, and the secondary formation, as well as the chemical and physical lifetimes of particles. As indicated by Wu et al. (2007, 2008), the level of particulate pollution in Beijing strongly depends on the meteorological conditions, especially the local wind speed and direction. This means that we cannot simply compare the pollution level during Summit with the pollution level before and after.

According to the recorded meteorological data, there were obvious changes in the local meteorological conditions before, during, and after the Summit period. Figure 2 shows the time series of the measured local meteorological parameters. In the week before the Summit period, average ambient T and RH were about 18°C and 55%, respectively, i.e., much higher than respective values during the Summit period (~10°C and 21%). During Summit traffic restrictions, north/northeast wind dominated 91% of the time, and the wind speed varied from calm wind to 10–12 $\mathrm{m\,s^{-1}}$, whereas before and after Summit, the wind speed stayed at 0.5 to 4 $\mathrm{m\,s^{-1}}$. One may suspect these strongly varying meteorological conditions to have been the main cause of the reduction in particle concentrations during the Summit period.

In order to segregate possible meteorological effects and to quantify approximately the influence of the traffic control measures on aerosol size distributions and visibility, our long-term observational data were used. However, one should only compare the particle size distributions during Summit with those with similar source conditions (except vehicle emissions), under similar local meteorological conditions, and with similar regional air mass transport characteristics. The criteria for selecting the comparable data population, named as "non-Summit" period, are described in the following.

Source conditions. In general, domestic heating in Beijing starts in the beginning of November and ends by the end of March. According to the statistical analysis of the long-term particle size distributions, there are significant aerosol differences in March, compared to November, December, January and February. Particle number concentrations are generally higher in March than in the other four winter months and dust events occur more frequently in March. An inspection of the data showed that, even if November, December, January and February all were considered in the non-Summit reference data population, the data of November would dominate the selected data population due to the other criteria described later, e.g., the temperature criterion. Moreover, gas-to-particle conversion, including photochemical secondary particle formation, and condensation, are considered major sources of urban aerosol particles. The solar zenith angle and incident radiation are different at different times of year. In order to have similar photochemical and radiation conditions, a conservative decision was made to only choose the data measured in the Novembers of 2004, 2005, 2006 (three months, excluding the summit period).

Local meteorological conditions. Only local weather conditions dominated by northern (northeast through northwest) wind directions were considered both in Summit and non-Summit periods, because northern wind frequency was about 91% during the Summit period. Moreover, the data in November 2004, 2005, 2006 were also selected within the 90% ranges of the other meteorological parameters during the Summit time periods (10% extreme cases were excluded, cf. Table 1). The criteria for local meteorological conditions are summarized in Table 1.

Air mass transport characteristics. The 144 h back trajectories at 500 m at every hour in November 2004, 2005, and 2006, calculated with NOAA Hysplit model (Draxler and Rolph, 2003), were also considered as an additional criterion. First, the mean back trajectory during Summit period (latitude $\bar{\boldsymbol{X}}_{\text{Summit}}$, longitude $\bar{\boldsymbol{Y}}_{\text{Summit}}$ and elevation $\bar{\boldsymbol{Z}}_{\text{Summit}}$) was calculated. The distances (D_i) of individual back trajectories of Summit period and of non-Summit periods ($\boldsymbol{X}_i$, $\boldsymbol{Y}_i$, and $\boldsymbol{Z}_i$) to the mean back trajectory of Summit were evaluated. For each back trajectory hour j, the spherical angular distance (ξ_i^j) can be calculated as

$$\xi_i^j = \text{arcos}[\sin X_j^j \times \sin \bar{X}_{\text{Summit}}^j + \cos X_i^j \times \cos \bar{X}_{\text{Summit}}^j \times \cos(\bar{Y}_{\text{Summit}}^j - Y_i^j]. \tag{1}$$

The distance between two corresponding back trajectory points at hour j is

$$d_i^j = \{(w_\xi \times \xi_i^j)^2 + [w_Z \times (Z_i^j - \bar{Z}_{\text{Summit}}^j)]^2\}^{\frac{1}{2}}. \tag{2}$$

Here w_ξ and w_Z are the respective weighing factors of ξ_i^j and the difference of Z_i^j and $\bar{Z}_{\text{Summit}}^j$. The weighing factors were used because of different units of ξ_i^j and Z_i^j. In the present study, w_ξ and w_Z were respectively chosen as 1 and 6.31×10^{-4}, which were determined empirically by a sensitivity study in the air mass cluster analysis. Finally, the total distance between two back trajectories was determined as a summation of distance at each hour with linearly decaying weighing factors (u_j). This means that the nearest back trajectory point is the most important.

$$D_i = \sum_{j=1}^{j=144} u_j \times d_i^j, \qquad u_j = 1 - (j-1) \times \frac{1-0.2}{144-1} \tag{3}$$

The 95% quantile of the distances between back trajectories during Summit period to their mean trajectory is about 72. So, only data during non-Summit were chosen when the distance of its back trajectory to the mean back trajectory of Summit was smaller than 72. The average distances of Summit and non-Summit periods to the mean back trajectory were about 42 and 45, respectively. Therefore, we concluded that characteristics of the long-range or regional air mass transport during Summit and non-Summit data sets were similar.

According to these criteria, a statistically comparable data population was formed with similar emissions (except vehicle emissions) and under similar local and regional meteorological conditions compared to the Summit period. This newly formed data population was denoted as "non-Summit". Long-term statistical analysis does not support any "weekend effect" on particle number size distributions in Beijing (Wu et al., 2008). So on weekdays and weekends the same criteria were applied for the two data populations. After the overall selection, there were 376 and 730 data points in Summit and non-Summit periods, respectively. The time resolution was 10 min.

5 Influence of the traffic control measures on the aerosol size distribution

Local wind speed is one of the most important meteorology parameters controlling the level of air pollution. Therefore, for both Summit and non-Summit periods, we segregated the data populations into three subgroups with wind speeds ranging from 0 to 3 m s^{-1}, 3 to 6 m s^{-1} and larger than 6 m s^{-1}, respectively. These wind speed ranges were selected according to the similarities of particle number size distributions within different wind speed ranges. The number of data points in each wind speed subgroup

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is presented in Table 2. For later discussions concerning the particle formation, the respective condensational sinks (CS) were also calculated for each subgroup with the measured particle number size distribution and ambient temperature and relative humidity, following Kulmala et al. (1998) and Pirjola et al. (1998).

Figure 3 presents the comparison of average particle number and volume size distributions in Summit and non-Summit periods, respectively. The data populations are sorted by the local wind speed. Mean values and their standard deviations are given, too. Obvious discrepancies between these two data populations (Summit and non-Summit) can be seen. The statistical significance of the discrepancies between the means of the entire size distributions in each pair of subgroups were tested by a multivariate analysis of variance. The differences of the entire mean values of particle size distributions for the wind speed ranges of 0–3 m s^{-1} and 3–6 m s^{-1} (c.f. Fig. 3a–d) were statistically significant at 99% confidence level with dimension of the group means as 1. When the wind speed was larger than 6 m s^{-1}, the differences between Summit and non-Summit periods were not statistically significant due to the large variances and too few data points in non-Summit subgroup (cf. Table 2 and Fig. 3e–f). Thus the following discussion will mainly focus on the subgroups with wind speed lower than 6 m s^{-1}.

As can be seen in Fig. 3a–d, for different wind speed ranges, the shape of particle number size distributions of Summit and non-Summit were generally similar, especially for the sub-micrometer particles. The wind speed range of 0–3 m s^{-1} was the most important, because it best represented the Beijing local emissions and was less influenced by regional or long-range transport. The number size distributions of Summit and non-Summit periods both peaked around 100 nm, whereas the maxima of volume size distributions were at around 400–500 nm. Particles with diameters from 40 to 500 nm were considered to be most strongly influenced by the traffic emissions, due to both of primary emissions and secondary photochemical formation, condensation and coagulation. In Fig. 3a, the diameter range of 40 to 500 nm, the ratio of particle numbers during Summit and non-Summit periods stayed at about 40–60%. This means that with similar other emissions (except vehicle emissions) and under similar meteo-

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rology conditions, particle numbers in Aitken and accumulation modes went down by 40–60% during Summit period. Another interesting feature in Fig. 3a–b is that the number of coarse mode particles was also much lower during Summit compared with the non-Summit period. There might be two reasons for this phenomenon. First, since the wind speed was relatively low ($<3\,\mathrm{m\,s^{-1}}$), coarse mode particles were mainly due to local dust resuspension. During Summit, approximately 30% (~800 000) of the cities' 2.8 million vehicles were taken off the roads. This of course would result in a reduction of the resuspended road/street dust in Beijing. On the other hand, the idea of this traffic restriction was not only a rehearsal for the Olympics but also as a logistical support to make it easier for Summit participants to get around Beijing. It can be expected that for the latter purpose, the municipality would have made more efforts on the road/street cleaning as well as watering the road/street and the plants. These efforts would also contribute to reducing the resuspension of road dust.

When the wind speeds were 3 to 6 $\mathrm{m\,s^{-1}}$, particle number size distributions were significantly different from those of the lower wind speed subgroup (0–3 $\mathrm{m\,s^{-1}}$), not only in terms of the shape of the distributions but also in absolute number concentrations. Accompanied by a substantial decrease of particle number and surface in Aitken and accumulation modes, a sharp increase of nucleation mode particles was found during both Summit and non-Summit periods. Nevertheless a constant ratio of the particles concentrations from 40 to 500 nm between Summit and non-Summit periods existed (~60%), as shown in Fig. 3c–d. Also the particle number concentrations in the nucleation mode during Summit were about 60% of those during non-Summit period, while the condensational sinks decreased from 0.068 to 0.026 $\mathrm{s^{-1}}$. This might be explained by a reduction of gas phase emissions of vehicles, which were part of the precursors and essential for the atmospheric photochemical and particle formation, condensation and coagulation processes. Comparing Fig. 3b–c and Fig. 3a–b, obvious increases of coarse mode particle numbers with increasing wind speed were been found both during Summit and non-Summit periods. This is consistent with the variations of coarse mode particles discussed in Sect. 3. However, the concentrations of coarse mode particles were higher during Summit than during non-Summit periods. The time series of particle size distributions were checked, and it was found out that significantly higher particle concentrations in coarse mode occurred only in the late night and very early morning during Summit. This might be due to some changes in the regional or long-range transports. Compared to most of the back trajectories during the Summit period, the back trajectories with higher particle concentrations in the coarse mode during the night when wind speed ranging 3–6 $\mathrm{m\,s^{-1}}$ were mostly originated from more northern direction and subsided from about 2000 m since 40 h away from Beijing.

As indicated before, the difference of particle numbers during Summit and no-Summit periods when the wind speed higher than 6 $\mathrm{m\,s^{-1}}$ was not statistically significant. However, shape and concentration level for coarse mode particles were very similar. This may indicate similar characteristics of regional or long-range air mass transport. Moreover, very high numbers of nucleation mode particles (mainly with diameters smaller than 10 nm) were found during the Summit period (cf. Fig. 3e) when the wind speed was higher than 6 $\mathrm{m\,s^{-1}}$. The corresponding condensational sink was only about 0.012 $\mathrm{s^{-1}}$, i.e., lower than 0.02 $\mathrm{s^{-1}}$, the threshold for significant new particle formation events in Beijing when northerly wind dominated, suggested by Wehner et al. (2004) and Wu et al. (2007).

The reduction of particle emission and formation, especially in the Aitken and accumulation mode ranges, resulting from the decrease in vehicular traffic during the Summit (4–6 November 2006) provides an obvious explanation for the difference between the two data populations during Summit and non-Summit periods. The number concentration of the particles in Aitken and accumulation modes was reduced by 40–60% during the Summit period. As mentioned before in the motivation, in the urban area of Beijing, the primary emissions by vehicle sources contribute 6–7% of $PM_{2.5}$ mass while the secondary inorganic salts (secondary ammonium, sulfate and nitrate) contribute over 35% of $PM_{2.5}$, and secondary particulate organic matter contributes over 50% to $PM_{2.5}$ in Beijing during winter time. Vehicle emissions are one of the most important sources contributing the precursors of the gas-to-particle conversion process.

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Moreover, the secondary formation of particles is not linearly correlated with the source strength of the precursors. So, the 40-60% reduction in Aitken and accumulation mode particles during Summit period may be mainly due to a reduction of secondary particle sources.

6 Influence of the traffic control measures on visibility

Pollution by particulate matter is considered to be one of the most formidable air quality and public health issue in Beijing. The public expresses strong concerns about a decrease in “blue sky” days. “Blue sky” is closely related to the visual range, which is also one of the thorniest issues for the Olympics in Beijing 2008.

Since no qualified visibility observation was available, the improvement of visibility due to the traffic control measures has been estimated based on the light extinction of particle and gas phases. The average RH of Summit and non-Summit periods were about 21% and 34%, respectively. Particle hygroscopic growth factor at RH 40% in Beijing could only reach up to 1.01 in the winter time and the particles did not show obvious growth below RH 60% (J. Meier[1], personal communication). So particle number size distributions under dry conditions (RH<30%) were used to simulate the particle extinction coefficients (σ_{ep}) with a spherical Mie model (Bohren and Huffman, 1998). An effective medium refractive index was assumed as 1.52–0.025i. A time series of the optical equilibrium effective refractive indices was derived from an aerosol optical closure study based on in-situ intensive observations in January 2005 at the PKU site. 1.52–0.025i was an average of the retrieved values which resulted in an optimum fit between the measured and simulated particle scattering and absorption coefficients. According to the formulae introduced by Fröhlich and Shaw (1980) and Tomasi et al. (2005), the average Rayleigh scattering coefficients of gases (σ_{sg}) has been estimated to be about

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$12\,\mathrm{Mm}^{-1}$ for both Summit and non-Summit periods according to the recorded ambient temperature and pressure. Absorption of visible light by gases (σ_{ag}) is considered to be essentially due to NO_2 (Groblicki et al., 1981). The average concentration level of NO_2 in Beijing during winter time was estimated to about 40 ppb according to the NO_2 concentrations measured with a long-path absorption spectrometer (Qin et al., 2006) in the intensive measurement at the PKU site during January and February 2007 (Zhang and Su, 2007). Therefore, σ_{sg} at 550 nm was calculated to be about $13\,\mathrm{Mm}^{-1}$ for non-Summit period with $\sigma_{ag}=0.33\times[NO_2]$ (Groblicki et al., 1981). For the Summit period, a 40% reduction of NO_x was reported by Wang et al. (2007), associated with the 30% vehicles taking off the road. If we assume that there was also about 30% reduction of NO_2 concentration during Summit, compared with the concentration of 40 ppb during non-Summit period, the absorption of NO_2 at 550 nm during Summit would be about $9.2\,\mathrm{Mm}^{-1}$. The calculated optical parameters of particle and gas phases are summarized in Table 3. It is worth noticing that when wind speed lower than $3\,\mathrm{m\,s}^{-1}$, over 95% particle extinction was contributed by the sub-1 μm particles. Still, with the wind speed within the range of 3–6 $\mathrm{m\,s}^{-1}$, submicrometer particles contributed about 78% and 93% to the total particle extinctions during Summit and non-Summit periods, respectively.

Consequently, an upper limit to the visibility (L_v, km) can be estimated, using the total light extinction of particle and gas phases ($\sigma_e=\sigma_{ep}+\sigma_{eg}$, Mm^{-1}) and a modified Koschmieder relation of $L_v=1.9\times10^3/\sigma_e$ (Griffing, 1980; Husar et al., 2000; Schichtel et al., 2001; Carrico et al., 2003). The Koschmieder constant of 1.9 is about half of the standard value (3.92) (Seinfeld and Pandis, 1998). The factor of two reduction considers the fact that real visual targets are not black, that they are frequently too small in size, and that they are located only at quantized distances away from the observer (Griffing, 1980). Since the comparison of size distributions when wind speed higher than $6\,\mathrm{m\,s}^{-1}$ was not statistically significant, we only discuss here the influence on the visibility by traffic control measures for the cases when wind speed was lower than $6\,\mathrm{m\,s}^{-1}$.

The estimated average visual ranges during Summit and non-Summit periods are

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presented in Table 3 and Fig. 4 for the wind speed ranges of 0–3 and 3–6 $m\,s^{-1}$. Compared with non-Summit periods, significant improvement of visibilities during the Summit period was found. According to the estimate in Fig. 4, if no traffic restriction had been in place during the Summit period, the average visual range during 4–6 November 2006 would have been lower by about 50%. This result is most important during relatively low wind speed. We note that even with normal traffic on the road, when wind speed was higher than 3 $m\,s^{-1}$, the visual range was over 20 km (cf. Fig. 4). We also applied this rough visibility estimate to the long-term particle number size distributions and found that over 95% cases with visual range lower than 5 km during 2004 to 2007 occurred when the local wind speed was lower than 3 $m\,s^{-1}$. This may hint that traffic restriction measures will be efficient concerning the improvement of situations with serious low visibility in Beijing.

7 Conclusion and remarks

We conclude that traffic restrictions implemented during the Sino-African Summit have been remarkably successful in reducing the number concentration of aerosol particles, in particular Aitken and accumulation mode particles, and in improving the visibility. Concerning the important roles of atmospheric particles in public health, atmospheric heterogeneous chemistry and radiative forcing, as well as the emissions of NO_x and volatile organic compounds which are essential controllers of lower tropospheric ozone, our analysis suggests that traffic restrictions could be effective in improving the air quality and reversing the climate change in Beijing and its surrounding areas.

The influence of traffic restriction in Beijing on the particle concentrations differs for different particle sizes. More significant effects on fine particles with diameters ranging from 40 to 800 nm have been found. Based on statistical analysis of long-term observation, under certain weather conditions, the source strength of the particles in Aitken and accumulation modes was reduced by 40–60% during the period of 4 to 6 November 2006, when the traffic restrictions were in place. This may be mainly due to the

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reduction on the secondary particle source. We note that our size-dependent aerosol data indicate that current measures led to reductions in particulate air pollution in the optically most important size range, whereas further vehicle control measures may lead to an increase in ultrafine particle formation from the gas phase if the condensational sink decreased further. Because other than northerly wind specific discussed in the present study, particle formation events can happen with much higher condensational sink (0.02–0.08 s^{-1}) and lower wind speed if the air mass is mainly coming from the south of Beijing (Wu et al., 2007).

If we assume that there were no traffic restrictions taking place and with normal level of the vehicle emissions during the Summit period, the visibilities during 4–6 November 2006 would have been lower by about 50%. This is especially important during relatively low wind speed. The importance of the present study is highest when the wind speed is lower than 3 $m\,s^{-1}$. The fact that over 95% cases with visual range lower than 5 km during 2004 to 2007 were occurred when the local wind speed was lower than 3 $m\,s^{-1}$ may suggest that traffic restriction measures will be efficient concerning the improvement of serious low visibility situations in Beijing.

This case study focused on the “relative” influence of traffic restriction on particle size distribution and visibility, thus the uncertainties of the quantified effects are not expected to influence significantly conclusions drawn from the present statistical analysis. We emphasize, however, that specific weather conditions ruled the Summit period, so a restricted application of the results is suggested.

The vehicle emission standard is improving in Beijing, and the new National IV standard implemented on 1 March 2008 is similar to Euro IV standard (Xinhua-News, 2008). However, new car registrations in Beijing keep growing by about 15% annually. A continuation of this increase may still cause intractable air quality problem in Beijing and its surrounding area in the near future. It is anticipated that Beijing prepares to test the readiness as a host of Olympics 2008 (China-Daily, 2006). Coordinated observations of multiple atmospheric species combined with satellite remote sensing, and modeling studies on such occasions can provide unique opportunities to validate and improve

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our understanding of atmospheric chemistry and physics not only for Beijing area but also for the large region of northeastern China even East Asia (Wang et al., 2007), and it will also helpfully support the implementing strategies to cope with the air pollution in Beijing.

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Table 1. Criteria of local meteorological conditions and distance to the mean back trajectory of Summit period.

Wind Direction		Relative Humidity	Ambient Temperature	Ambient Air Pressure	Distance to the mean Back Trajectories
0°–60°	Lower Limit†	9%	4.4°C	999.2 mbar	0
300°–360°	Upper Limit†	60%	18.2°C	1014.2 mbar	72.0

† The lower and upper limits are taken as 5% and 95% quantile of respective data during the Summit periods.

Table 2. Number of data points in each wind speed subgroup during Summit and non-Summit periods.

	Total	0–3 m s^{-1}	3–6 m s^{-1}	>6 m s^{-1}
Summit	376	100	130	146
non-Summit	730	540	180	10

Table 3. Simulated optical parameters of particle and gas phases at 550 nm, as well as the visual ranges during Summit and non-Summit periods.

	0–3 m s^{-1}		3–6 m s^{-1}	
	Summit	non-Summit	Summit	Non-Summit
Extinction of particle phase [Mm^{-1}]				
Sub-1 μm	340	690	19	53
Super-1 μm	11	30	5.5	3.5
Total	350	720	24	57
Extinction of gas phase [Mm^{-1}]				
Rayleigh scattering	12	12	12	12
NO_2 absorption	9.2	13	9.2	13
Total	19	25	19	25
Visual Range [km]	5.2	2.6	42	23

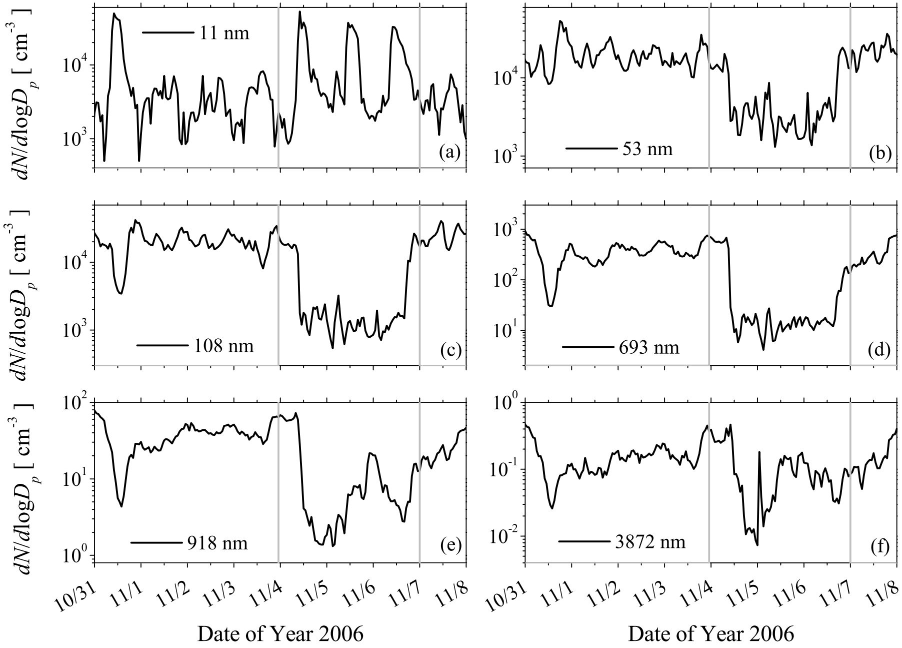

Fig. 1. Time series of particle numbers at different diameters in October and November 2006 at the PKU site on the campus of Peking University, Beijing.

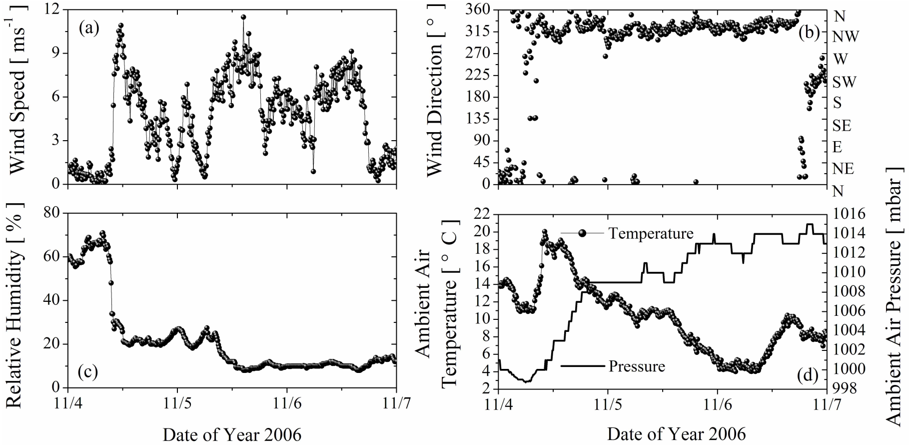

Fig. 2. Local meteorological parameters include wind speed **(a)**, wind direction **(b)**, relative humidity **(c)**, and ambient air temperature and pressure **(d)** near the PKU site during the Summit period (4 to 6 November 2006). The resolution of the presented data sets is 1 h.

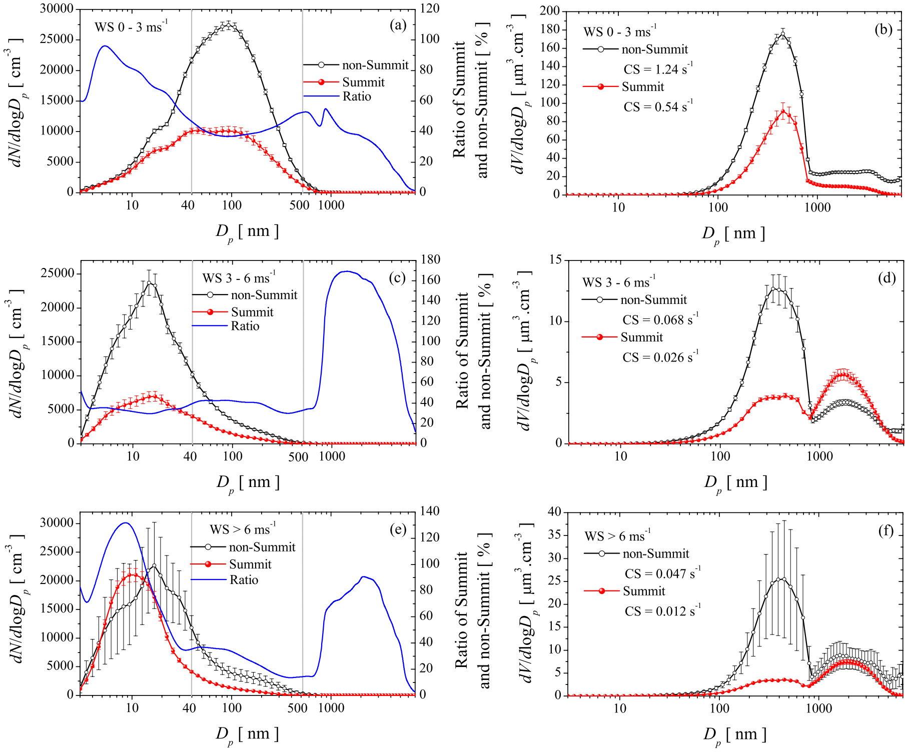

Fig. 3. Comparison of aerosol particle number and volume size distributions for Summit and non-Summit periods. The data are sorted by the local wind speed. Standard deviations about the mean values are given as error bars. The average condensational sinks (CS) are also given.

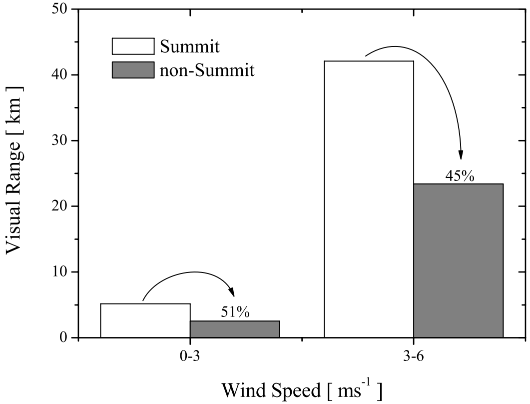

Fig. 4. Estimated visual range due to the extinction of particle and gas phases during Summit and non-Summit periods.

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