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Beijing Olympics as an aerosol field experiment

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[1] During the 2008 Olympic Summer Games, emission reductions were enforced in Beijing to improve air quality. Here we explore their effect on the regional aerosol load. We compare satellite-retrieved aerosol optical thickness (AOT) of that period with previous years, both in absolute terms and in a neural network approach taking into account the meteorological conditions. A statistically significant reduction of aerosol load is found in Beijing that decreases in magnitude and significance with increasing region size. Locally, the aerosol load ($log(AOT)$) was about 0.4 to 0.75 standard deviations below the levels expected for the prevailing meteorological situation. The small size of this effect relative to meteorological variability highlights the importance of regional aerosol transport.
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1. Introduction

[2] The effect of aerosols is one of the major remaining uncertainties in our understanding of the global climate system and in climate models [*Anderson et al.*, 2003]. Patterns of aerosol distribution in time and space are shaped by the locations of aerosol sources, circulation patterns and removal processes. While an anthropogenic contribution to aerosols in the atmosphere is undisputed, large-scale measurement of its magnitude is not possible normally. The period of the Olympic and Paralympic Summer Games held in Beijing, China during August and September 2008 provided a rare exception: Extensive provisions to improve air quality created a unique opportunity for studying the anthropogenic contribution to the atmospheric aerosol load.

[3] Beijing is set in a heavily industrialized and urbanized region, with a population of more than 10 million on an area of about 17,000 km^2. The city is known for its high levels of air pollution and permanently hazy skies [*Streets et al.*, 2007; *Chan and Yao*, 2008]. According to previous studies, aerosols in the Beijing region are from local pollution sources as well as from various remote sources [*An et al.*, 2007]; desert dust transport adds to Beijing aerosol primarily in spring [*Eck et al.*, 2005].

[4] In order to improve air quality for the 2008 Summer Games, the Chinese government imposed a number of measures in Beijing to reduce the emissions of pollution aerosol. These included temporary closures of factories and restrictions on traffic. Only one half of the about 3.3 million registered cars were allowed on the roads each day. The measures were in place from 20 July to 20 September 2008. Within a radius of about 150 km around Beijing, similar but less extensive traffic and industry restrictions were imposed (cf. The New York Times, 1 August 2008).

[5] Similar traffic restrictions aimed at improving air quality had been implemented during a three-day political summit in November 2006. *Cheng et al.* [2008] analysed corresponding surface air pollution levels, finding particle concentration reductions of 40 to 60%. The 2008 Summer Games period provides the opportunity to study the impact of reduced emissions on atmospheric aerosol load on a much larger time scale. Accordingly, the aim of this study is to assess the effect of the air quality measures taken in summer 2008 on the total integrated column atmospheric aerosol load, i.e. aerosol optical thickness (AOT), in Beijing and the surrounding region. While AOT may not be representative of surface conditions due to variations in vertical aerosol distribution, this assessment does provide an interesting insight into the anthropogenic contribution to total atmospheric aerosol load.

[6] Official projections of the relative reduction of Olympic Games period traffic and industrial emissions existed (60–70% for traffic, 'up to' 30% for industry, http://2008.bjjtw.gov.cn). However, the authors have no information on the absolute magnitude of the emissions with and without the measures, and on how much of the reduction target was actually achieved. Even if the daily mass reduction was known, the conversion to AOT would require precise knowledge of mass extinction efficiency and thus aerosol species composition. Given all these parameters, AOT reduction could be computed directly. In this study, the opposite route is chosen: Not knowing the magnitude of the emissions reduction we try to quantify the effect of the measures on total atmospheric aerosol. As the Beijing restrictions on traffic and industry can be seen as 'best effort' environmental action, this study highlights the potential of such short-term political measures to impact atmospheric aerosol load.

2. Data and Methods

[7] In order to analyse the effect of the Olympic Games measures, data for summer 2008 as well as the previous summers was needed. For 2008, the period from 1 August to 19 September was used. This time frame was chosen because it begins a few days after the start of the air quality measures (20 July) and ends on the last day they were in place. For the previous summers, data covering the same period were used. Based on data availability, the years 2002 to 2007 served as the reference period.

[8] For the analysis of aerosol load the aerosol optical thickness (AOT) product based on Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Terra

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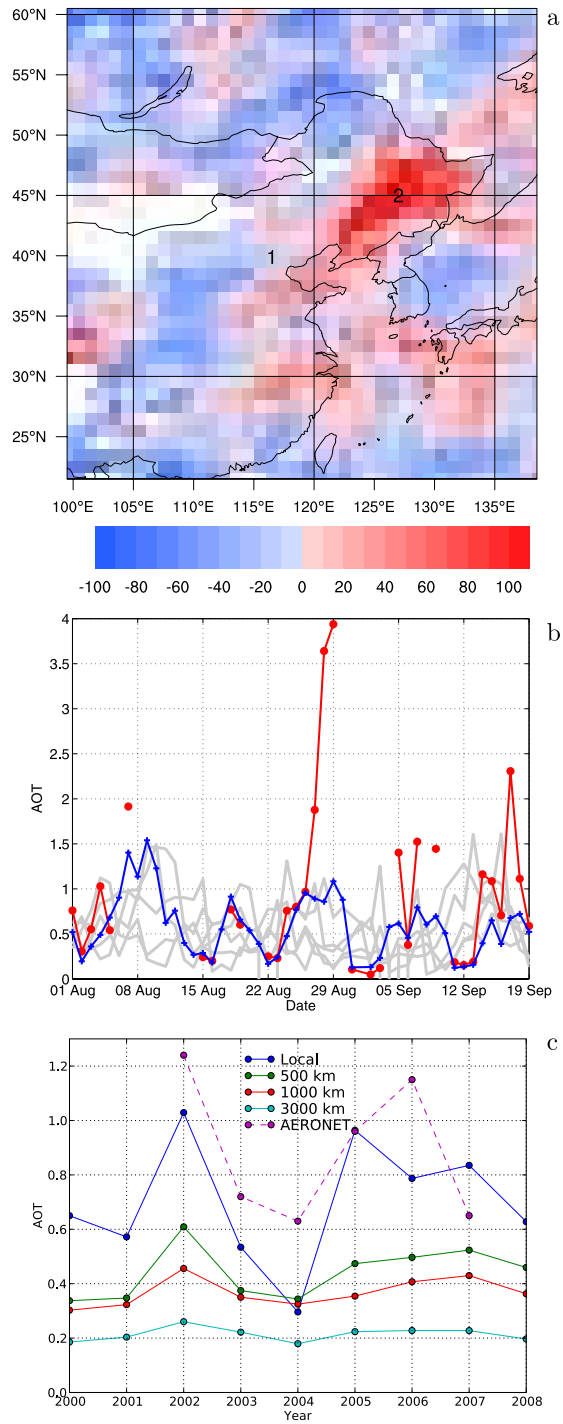

Figure 1. (a) August 2008 mean AOT vs. mean August AOT in the reference period (2002–2007). The relative change is given in percent (difference divided by reference period mean); negative values indicate a smaller AOT in 2008. White pixels are missing data. Numbers are explained in the text. (b) Development of Beijing AOT over the summer of 2008 (red, with dots, 1° MODIS data) and mean daily AOT of a 500 km radius region (blue, with crosses). The 500 km mean daily AOT values of the years 2002–2007 are given in grey. All MODIS AOT data used in the paper is AOT at 0.55 μm. (c) August MODIS AOT data from 2000 to 2008 for four region sizes around Beijing (radius in km; 'local' refers to the 1° grid cell at the location of Beijing) and AERONET AOT at Beijing (at 0.5 μm).

Table 1. Changes in Mean AOT (0.55 μm), August 2008 ($\overline{AOT_{2008}}$) Versus Average of Previous Years (2002–2007) ($\overline{AOT_{ref}}$), Computed As a Difference ($\overline{AOT_{2008}} - \overline{AOT_{ref}}$) for Various Region Sizes[a]

	Local	150	300	400	500	1000	3000
Deviation (%)	−11.35	−14.73	−1.83	0.86	3.28	3.02	−9.03
Deviation (σ_{ref})	−0.35	−0.51	−0.05	0.04	0.09	0.02	−0.18

[a]Column heads give radius around Beijing in km. Here σ_{ref} is the standard deviation of the August AOT means of the reference period (2002–2007).

platform was chosen (MOD08, collection 5) [*Remer et al.*, 2005].

[9] Aerosol load depends on emission source location and strength. In addition, meteorological conditions, especially wind speed and direction, relative humidity and precipitation lead to a significant modification of aerosol load [cf. *Wu et al.*, 2008]. Precipitation data was obtained from the Tropical Rainfall Measuring mission (TRMM) Real-Time Multi-Satellite Precipitation Analysis [*Huffman et al.*, 2007]. European Centre for Medium-Range Weather Forecasts (ECMWF) analysis data [*Uppala et al.*, 2005] was used as a source of all other meteorological information.

[10] All data sets were either available at or reduced to a daily resolution on a 1° grid. At about 9500 km^2 the grid cells around Beijing (39.9°N, 116.4°E) are about half the size of the Beijing urban area.

[11] Data analysis was performed as follows: First, the mean 2008 August AOT was compared to the mean of the previous years to detect any anomalies in absolute aerosol load. The 2008 Olympic Games period was then considered in detail. Finally, a neural network was used to link aerosol load changes to meteorological conditions. It was trained with the meteorological and AOT data from the reference period (2002–2007) and subsequently used to predict the summer of 2008 (see section 3 and auxiliary material for details on the method).[1] Deviations of the observations from the values predicted for a situation without air quality measures were then analysed to determine the effective changes in aerosol load resulting from the emission reduction.

3. Analysis

[12] For an overview of the absolute aerosol load in summer 2008 as compared with previous years, the August Terra/MODIS AOT mean was contrasted with the average and standard deviation of the reference period August means. Figure 1a shows the relative change in August AOT. Beijing ('1' in the map) experienced reduced aerosol levels, while the surrounding areas display a mixed situation. Especially the north-east of China ('2') saw AOT increases over the reference period mean.

[13] Table 1 summarizes the changes in AOT as observed locally and averaged over regions with six different radii. AOT change was negative locally and at a distance of up to 150 km (up to above 14%), but only slightly negative to positive at most larger distances. The maximum reduction

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038572.

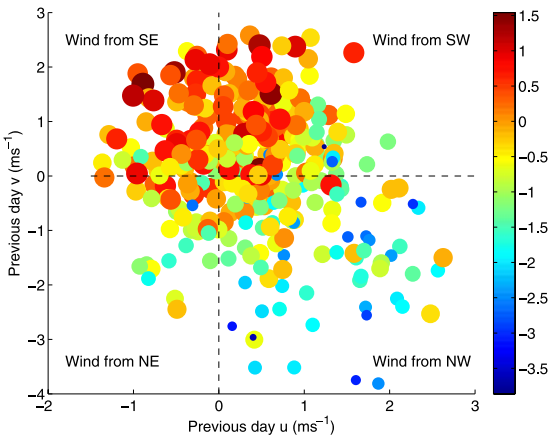

Figure 2. The *log*(*AOT*) as a function of previous day wind components for summer 2002–2007. In addition to the color scale, the size of the dots is also scaled with *log*(*AOT*). Here *u* is the eastward, and *v* is the northward wind velocity. Directions of wind origin are indicated in the quadrants.

relative to the reference period variations was half a standard deviation (150 km radius). While these data do show reduced aerosol levels, the spatial pattern shown in Figure 1a is ambiguous and a deviation of 0.5 standard deviations could be random variation. Therefore a more detailed analysis of the data series is warranted.

[14] Daily AOT values in the Olympic Games period fluctuated strongly, both in the Beijing 1° cell and in a wider region (Figure 1b). However, in contrast to other regions of the world there is no clear weekly cycle (cf. similar findings by *Xia et al.* [2008] and *Bäumer et al.* [2008]). While there is a small negative trend, this is not statistically significant. There are a few events with very large local AOT (e.g. 28 and 29 August 2008). These could be confirmed as realistic observations by analysis of Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) observations (for CALIOP, see *Winker et al.* [2007]) as well as in AERONET AOT data for Beijing and Xianghe (about 60 km east–south east of Beijing) (for AERONET, see *Holben et al.* [1998]). A discussion of AERONET vs. MODIS AOT is given in the auxiliary text as well as Figures S1 and S2. The local Beijing AOT values generally exceed the 500 km average. This is probably due to the concentration of pollution sources in the lowland region directly around Beijing and the blocking effect of the mountains to the north and west. This pattern is also seen in the interannual variations in Figure 1c showing MODIS AOT for the month of August for all years available. AOT in Beijing ('Local') varies strongly over the years. However, it does not display a clear trend in this time period that would indicate a change in emissions over the 2002–2008 period.

[15] In order to determine whether the Olympic Games air quality measures effectively lowered AOT, the observed situation needs to be compared to what was to be expected given the meteorological situation. This was done using a neural network. Since AOT displays a clear log distribution [cf. *O'Neill et al.*, 2000], the natural logarithm of AOT (*log*(*AOT*)) was used in the neural network analysis. To determine the importance of each meteorological parameter in predicting *log*(*AOT*), the correlations of each parameter with *log*(*AOT*) were computed. This analysis revealed the strongest relationships for previous day and same day u and v components of wind (eastward and northward velocities), with absolute correlations of 0.39 to 0.59. Figure 2 shows the relationship between previous day wind components and *log*(*AOT*). Clearly, (light) southerly to south–easterly winds appear to favor large *log*(*AOT*). This seems sensible, as the industrial cities of Tianjin and Tangshan lie in that direction, at a distance of only about 100–150 km from Beijing. *Garland et al.* [2009] observe a similar pattern. In situations with strong winds, mostly from the north–west, AOT is noticeably lower. This is in accordance with findings by *Wu et al.* [2008].

[16] A feed-forward backpropagation neural network was built to relate *log*(*AOT*) to wind components (u, v, previous day u, previous day v), precipitation and relative humidity. Three quarters of the reference period data were used for network training (n_t = 164), the remaining quarter (selected at random) for validation (n_v = 55). The network consists of two neurons and one hidden layer. Using the 2008 meteorological observations (n_{2008} = 31), *log*(*AOT*) was predicted for the Olympic Games period and compared to the Terra/MODIS observations. Thus the neural network essentially predicts the aerosol load expected for the summer 2008 meteorological conditions, assuming no air quality measures. The difference to the observed values can then be attributed to the restrictions imposed during the Olympics.

[17] Figure 3 shows the probability density functions (pdf) of *log*(*AOT*) as predicted and observed locally for Beijing. While the distribution of the daily values in the validation data set (Figure 3 (right), selected at random from summers 2002–2007) matches the position of the corresponding predictions, summer 2008 daily values (Figure 3 (left)) are clearly shifted towards lower values compared to predicted.

[18] Predictions and observations were compared for the local observations as well as regions surrounding Beijing with radii from 150 to 3000 km. Table 2 summarizes the results. The analysis shows that *log*(*AOT*) in Beijing was reduced locally by about 14% compared to levels expected in the same meteorological situation without emission controls. This corresponds to 0.73 standard deviations of the predicted *log*(*AOT*) data. The deviation is statistically significant at the 95% level (Student's t test). The validation data set in contrast was well represented by the prediction,

Table 2. Output From the Neural Network Simulations Versus Measured *log*(*AOT*)[a]

	Local	150	300	400	500	1000	3000
Median deviation (%)	−13.7	−12.0	−13.7	−9.1	−7.5	−11.8	0.7
Median deviation (σ)	−0.73	−0.41	−0.31	−0.36	−0.39	−0.43	0.08
C_v	0.79	0.82	0.84	0.70	0.71	0.67	0.37
$P(t)$	0.00	0.01	0.27	0.19	0.08	0.01	0.47
$n(P(t) < 0.05)$	8	8	0	0	0	8	2

[a]The columns are regions of varying radii (given in km). Here σ is the standard deviation of predicted *log*(*AOT*), C_v is the correlation of network output with the validation data set, and $P(t)$ is the probability that the predicted and observed *log*(*AOT*) values belong to the same distribution (Student's t test). Here $n(P(t) < 0.05)$ gives the number of cases in which $P(t)$ was smaller than or equal to 0.05 out of 10 model training repeats.

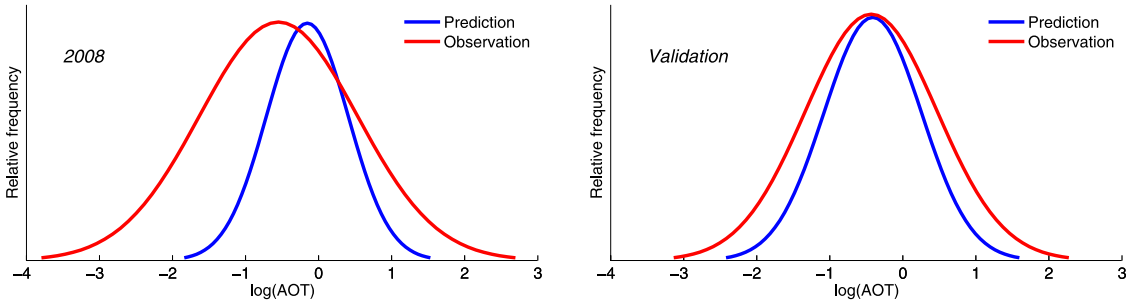

Figure 3. Probability density functions (pdf) of daily *log*(*AOT*) observations (red) and predicted values (blue) for Beijing (local grid cell): (left) summer 2008 and (right) validation data set (randomly chosen from summers 2002–2007).

with a correlation of 0.79 and a successful t test (not shown). Model training and assessment was repeated 10 consecutive times, in 8 of which a significant deviation (of about the same magnitude) was noted ($n(P(t) < 0.05)$ in Table 2).

[19] As the size of the region is increased, a reduced aerosol load continues to be detected, in contrast to the comparison independent of meteorological context shown above. However, the relative magnitude (mean deviation expressed in standard deviations) and statistical significance ($P(t)$, $n(P(t) < 0.05)$) decrease notably with region size, as shown in Table 2. While at a 1000 km radius the deviation from the predicted values is significant in most neural network simulations, the model itself is poor (correlation with the validation data of 0.67). An aerosol load reduction is detected with the greatest significance locally and within a 150 km radius. Larger regions seem to display a reduction relative to the expected as well, although the statistical reliability is smaller. The distribution is particularly wide for the 3000 km region and much less ambiguous for smaller regions.

4. Conclusions

[20] The analysis of summer 2008 aerosol optical thickness in the Beijing region shows that measures taken during the Olympic Summer Games very likely had a noticeable effect. This effect is not immediately clear from the absolute numbers due to high variability resulting from meteorological conditions. However, the neural network analysis considering weather patterns reveals a statistically significant deviation of 2008 column aerosol levels compared to what was to be expected without emission reductions.

[21] However, the magnitude of the aerosol load reduction was rather low compared to meteorological variability, at 10 to 15%, or 0.4 to 0.75 standard deviations. Also the effect was statistically significant only in Beijing and the immediate surroundings. While this may be disappointing, it is not surprising, as the importance of regional aerosol transport has been emphasized before [*Charlson et al.*, 1974]. While air quality measures were implemented in a region of about 100–200 km diameter, aerosol pollution operates on a scale of more than 1000 km.

[22] A limited spatial resolution of 1 degree and possible inaccuracies in the data may impair interpretability of the results. The MODIS aerosol product may discard thick non-absorbing aerosol layers as clouds and thus might be slightly biased towards low AOT. This could lead to an underestimation of the aerosol load reduction. However, this error is rare [*Remer et al.*, 2005] and should not distort the nature of the findings.

[23] This analysis of the summer 2008 situation thus gives a first idea of the effect reductions of anthropogenic emissions can have on aerosol load. It highlights the importance of treating aerosol pollution as a regional phenomenon. The findings of the current study may not be representative at ground level and thus cannot be interpreted directly in terms of surface air quality. More detailed studies, possibly accounting for aerosol properties and trajectories during the 2008 Olympics, will contribute to a clearer picture of what measures would be required to permanently improve air quality in Beijing.

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