Traffic restrictions associated with the Sino-African summit: Reductions of NO_x detected from space

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[1] Aggressive measures were instituted by the Beijing municipal authorities to restrict vehicular traffic in the Chinese capital during the recent Sino-African Summit. We show that reductions in associated emissions of NO_x were detected by the Dutch-Finnish Ozone Monitoring Instrument (OMI) aboard the Aura satellite. Interpretation of these data using a 3-dimensional chemical transport model indicates that emissions of NO_x were reduced by 40% over the period of November 4 to 6, 2006, for which the restrictions were in place. **Citation:** Wang, Y., M. B. McElroy, K. F. Boersma, H. J. Eskes, and J. P. Veefkind (2007), Traffic restrictions associated with the Sino-African summit: Reductions of NO_x detected from space, *Geophys. Res. Lett.*, *34*, L08814, doi:10.1029/2007GL029326.

1. Introduction

[2] A variety of studies have been published in recent years exploring implications for local, regional and global air quality of emissions of pollutants from China [*Y. X. Wang et al.*, 2004; *Wang et al.*, 2006]. A persistent problem has been to reconcile estimates of emissions based on bottom-up studies [*Streets et al.*, 2003] with concentrations of chemical species observed in the atmosphere [*Wang et al.*, 2003; *T. Wang et al.*, 2004]. Emissions required to account for observations of CO and NO_x ($NO + NO_2$) (inferred from application of 3-d models in an inverse mode) were significantly higher than emissions derived using the bottom-up approach. The discrepancy in the case of CO appears to have been resolved by upward revision [*Streets et al.*, 2006] of the bottom-up inventory accounting for industrial sources omitted in the earlier analysis. The influence of a large microbial source has been suggested to account for the discrepancy in the case of NO_x on the regional scale [*McElroy and Wang*, 2005; *Wang et al.*, 2007].

[3] The Summit of the Forum on China-Africa Co-operation (FOCAC), convened in Beijing on 4 and 5 November 2006, offers an interesting opportunity to test current understanding of emissions of NO_x from the Beijing environment. The Summit involved the largest international gathering to take place in China since 1949, with high-level participants from 48 African countries. Major initiatives were taken to limit traffic in Beijing over the period November 1 to 6, both to accommodate the Summit but also to serve as a dress rehearsal for the 2008 Olympic Games. While the public was advised to drive less for six days, specific and mandatory regulations were instituted only between November 4th and 6th (Beijing Traffic Management Bureau, http://www.bjjtgl.gov.cn/Article_tg.asp?AE_ID=418, in Chinese). Bus transport capacity was increased, access to specific roads was limited, and bans were instituted on use of government and commercial vehicles with restrictions also on private vehicles. News reports suggest that approximately 30%, or 800,000, of the city's 2.82 million vehicles were taken off the roads as a result of measures adopted during the Summit by the Beijing municipal authorities (China Daily, http://www.chinadaily.com.cn/2008/2006-11/07/content_726767.htm). As a result of these initiatives, one might expect a significant decrease in emissions of NO_x from the transportation sector. We show in what follows that a reduction in NO_x emissions was in fact observed by the Ozone Monitoring Instrument (OMI) aboard the EOS Aura satellite and that these observations, in combination with a model analysis, can be used to obtain a quantitative estimate of the magnitude of this reduction.

2. OMI NO_2 Columns and GEOS-Chem Simulation

[4] The Dutch-Finnish OMI is a nadir-viewing imaging spectrograph measuring direct and atmospherically backscattered sunlight in the spectral range 270 nm to 500 nm [*Levelt et al.*, 2006a, 2006b], from which information on several trace gases, including NO_2 [*Bucsela et al.*, 2006] is derived. The Aura satellite is on a polar sun-synchronous orbit crossing the equator at 0145 and 1345 local time. Compared with its predecessors GOME and SCIAMACHY, OMI has the advantage of daily global coverage and small pixel size (24×13 km^2 in the nadir). The near-real time (NRT) retrieval of tropospheric NO_2 columns from OMI is based on the combined retrieval-assimilation-modeling approach developed at the Royal Netherlands Meteorological Institute (KNMI) [*Boersma et al.*, 2004]. The NRT availability of stratospheric slant columns and NO_2 profiles is achieved using the TM4 chemistry transport model exercised in a forward time mode based on forecast ECMWF (European Center for Medium Range Weather Forecasting) meteorology and NO_2 information assimilated from prior orbits [*Boersma et al.*, 2006]. The 1-sigma uncertainty in NO_2 columns for individual OMI retrievals is estimated at $\pm 0.5 - 1.5 \times 10^{15}$ molecules/cm^2 associated with spectral fitting with a relative error of between 10% and 40% attributed to uncertainties in calculation of air mass factors [*Boersma et al.*, 2006].

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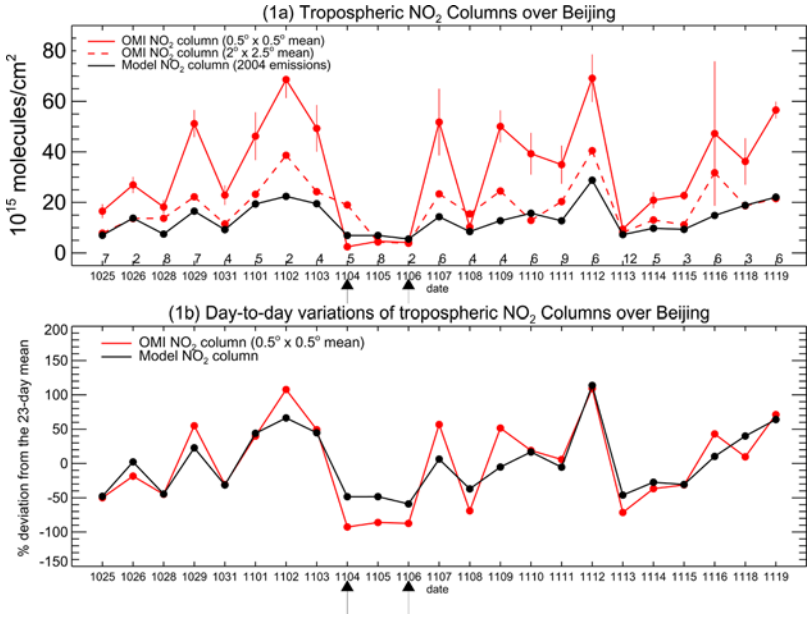

Figure 1. Tropospheric vertical columns of NO_2 over Beijing between October 25 and November 19, 2006. OMI data were averages between 1 pm and 3 pm local time as the satellite overpasses Beijing. No data were available from OMI over the Beijing region on October 30 and November 17, 2006. Arrows indicate the period of mandatory traffic restrictions. (a) Mean OMI columns with standard deviations by averaging multiple OMI pixels over two horizontal scales surrounding Beijing: 0.5° × 0.5° (solid red) and 2° × 2.5° (dashed red). The number of OMI pixels selected for averaging on the 0.5° × 0.5° grid is shown at the bottom for individual days. NO_2 columns simulated by the GEOS-Chem model using 2004 emissions and sampled at the overpass time of OMI are shown in black. (b) Day-to-day variations of NO_2 columns from OMI on the 0.5° × 0.5° grid (red) and the GEOS-Chem model (black). Data shown are percentage deviations from the mean columns for the 23-day period. The mean columns for OMI and the model were calculated separately.

[5] Column densities of NO_2 derived from OMI for Beijing for the period October 25 and November 19, 2006, are presented in Figure 1a. These results were obtained by averaging multiple OMI pixels over two horizontal scales for the region surrounding Beijing (39.9°N, 106.25°E), 0.5° (lat) × 0.5° (long) and 2° × 2.5°, the finer resolution reflecting the approximate size of the Beijing urban area, with the coarser averaging appropriate for the resolution of the chemical transport model described below. Pixels for which cloud radiance fractions exceeded 50% were excluded from the present analysis. Averaging over multiple pixels is expected to reduce the influence of random errors associated with individual retrievals. A notable feature of the results in Figure 1a is the relatively low column densities of NO_2 observed between November 4th and 6th, coinciding with the traffic restrictions instituted during the Summit and significantly lower (by about a factor of two) than other time periods with relatively low NO_2 (e.g., 13–15 Nov). Day-to-day variability in column densities reflects presumably a combination of changes in emissions and changes due to variations in meteorological conditions and the chemical lifetime of NO_2. It will be shown below that the reduced NO_2 concentrations on 4–6 Nov can be attributed to reduction in NO_x sources. Differences between weekday and weekend emissions have been shown to drive a "weekend effect" in NO_2 columns observed from space over industrialized regions and cities in the US, Europe and Japan: no such effect has been observed for China [*Beirle et al.*, 2003].

[6] Since spatial averaging tends to smear contributions from "hot" spots corresponding to high emissions with those from surrounding regions distinguished by lower emissions, column densities inferred for the higher resolu-

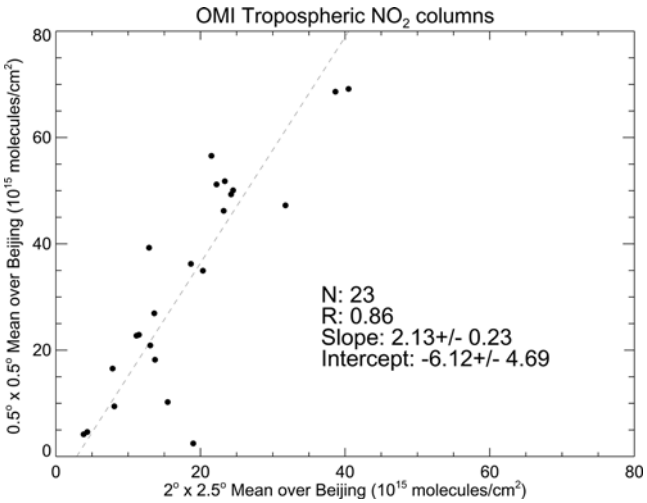

Figure 2. Relationship between tropospheric NO_2 columns derived from OMI on two spatial scales surrounding Beijing: 0.5° × 0.5° (y-axis) versus 2° × 2.5° (x-axis). Data are for the period between October 25 and November 19, 2006. The correlation coefficient (R) and slope of the reduced-major-axis regression line are shown.

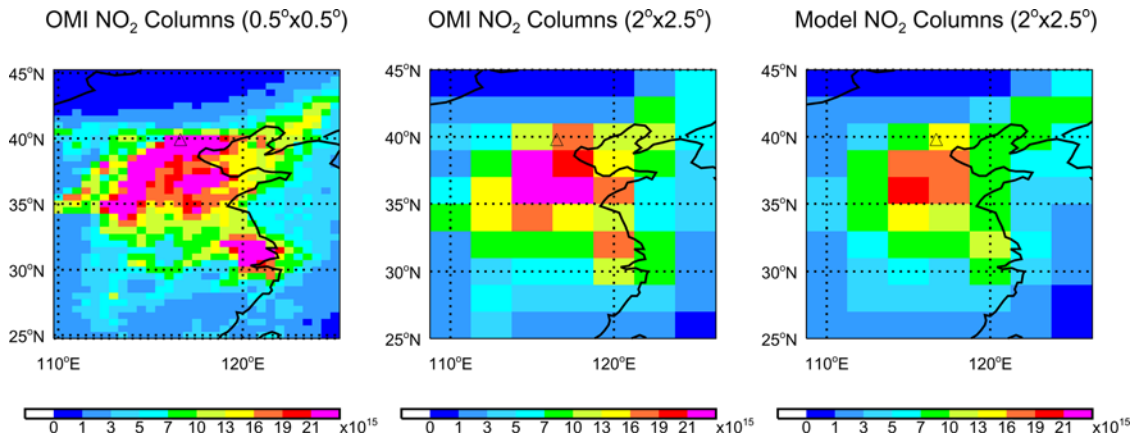

Figure 3. Tropospheric NO_2 columns (unit: molecules/cm^2) over east China averaged between October 25 and November 19, 2006. OMI columns are shown with resolutions of (left) 0.5° × 0.5° and (middle) 2° × 2.5°. (right) NO_2 columns simulated by the GEOS-Chem model using 2004 emission inventory are shown with the resolution of 2° × 2.5°. Model values are sampled at the overpass time of OMI. Location of Beijing is indicated by the black triangle. Integrated amounts of tropospheric NO_2 on land over the domain are 2.2×10^{32} molecules for OMI data (Figures 3, left, and 3, middle) and 1.8×10^{32} molecules for the model (Figure 3, right).

tion (0.5° × 0.5°) grid are characteristically higher than those for the lower resolution (2° × 2.5°) presentation. Temporal variations in NO_2 on the two spatial scales are well correlated, however, as indicated in Figure 2, implying that the physical and chemical processes responsible for the changes in NO_2 columns observed on the two scales are similar, suggesting that results obtained using the model with a resolution of 2° × 2.5° may be scaled to provide a simulation of conditions on the higher resolution available from OMI (0.5° × 0.5°).

[7] We conduct a simulation between October 1st and November 19th 2006 using the GEOS-Chem global 3-D model for tropospheric chemistry, driven by the first-look data of the GEOS-4 assimilated meteorological observations, with a horizontal resolution of 2° latitude by 2.5° longitude and 30 vertical sigma levels, extending from the surface to 0.01 hPa. The model assumed an inventory of emissions available for 2004. Details of the model simulation are provided in the auxiliary material.[1] The temporal variation of columns densities obtained using the GEOS-Chem model is compared with the observational data in Figure 1b. Absolute values of model column densities are included in Figure 1a. Model results displayed here refer to the time of day corresponding to overpasses of OMI (between 1 pm and 3 pm local time over Beijing). The temporal correlation between model and OMI is impressive, especially so since emissions were taken as constant for purposes of the model simulations: the correlation coefficient (R) approaches 0.9 (n = 23) for both presentations of the OMI data (low and high resolution). This suggests that the day-to-day variations in NO_2 indicated here are driven primarily by changes in meteorology and chemistry, features that are accurately reproduced by the model. The model is successful in accounting not only for the pattern of variations observed in the immediate vicinity of Beijing but also for observations over the larger region of East China (Figure 3). When OMI pixels are averaged over the spatial grid corresponding to the model resolution, the spatial correlation between model and OMI for the entire region is 0.9 (n = 70).

[8] Column densities predicted by the model for the Beijing region (using the emission inventory available for 2004) are generally lower than values inferred from OMI except for the period 4–6 November (when traffic restrictions were in place). Weather conditions in the Beijing region were not particularly unusual over this period (Figure S1 in the auxiliary material). Moreover, skies were generally clear over Beijing for most of the interval covered by the data in Figure 1. A reduction in NO_x emissions resulting from the decrease in vehicular traffic during the Summit provides an obvious explanation for the discrepancy between model and observation detected between November 4 and 6.

3. Changes in Emissions of NO_x During the Traffic Control

[9] Three factors contribute to the changes in column densities of NO_2 observed over any particular region for any particular interval of time: changes in emissions of NO_x, changes in the chemical lifetime of NO_x, and changes in the horizontal divergence of the flux of NO_x (differences in flow into and out of the region). Accounting for mass balance, the relative change in NO_2 column densities, $\frac{1}{C}\frac{dC}{dt}$, may be represented by

$$\frac{1}{C}\frac{dC}{dt} = \frac{E}{C}\mathrm{R} - \frac{1}{\tau_{chem}} - \frac{1}{\tau_{tran}} \quad (1)$$

where C denotes the column density of NO_2, E denotes emissions of NO_x, τ_{chem} refers to the chemical lifetime of NO_x, τ_{tran} is a time scale associated with the horizontal divergence, and R defines the ratio of NO_2 to NO_x column densities. Given the success of the model in reproducing the observed relative variability of OMI columns (i.e., the left-hand side of equation (1)), we conclude that the model may

[1] Auxiliary materials are available in the HTML. doi:10.1029/2007GL029326.

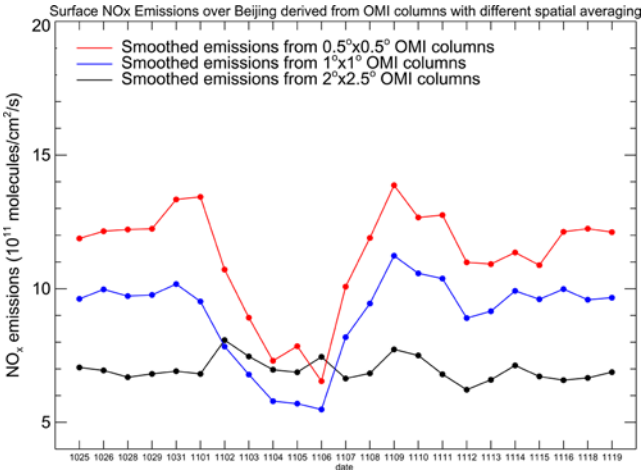

Figure 4. Surface emission fluxes of NO_x over Beijing inferred from OMI NO_2 columns averaged over three horizontal scales: 0.5° × 0.5° (red), 1° × 1° (blue), and 2° × 2.5° (black). The time series are smoothed by applying 5-day central moving averages.

be used to simulate contributions of individual terms on the right-hand side of equation (1). Since τ_{chem}, τ_{tran}, and R should not depend on assumptions made concerning the magnitude of emissions (nonlinearity introduced by changes of OH on τ_{chem} has been shown to be less than 5% over Beijing for the range of emissions applicable here [*Martin et al.*, 2006]; further discussion related to τ_{chem} is provided in the auxiliary material), we propose to use the relationship between E and C in the model to estimate the emissions of NO_x implied by the column densities measured by OMI. This approach has been applied previously to NO_2 using satellite observations for east China [*Wang et al.*, 2007] and for other parts of the globe [*Martin et al.*, 2006] and have been shown to provide a reliable means to determine the strength of relevant emissions.

[10] Emissions of NO_x (molecules/cm^2/s) inferred from the data are presented in Figure 4. A 5-day central moving average was applied on the emissions to remove random variations inherent in the time series in order to highlight the underlying trend. Use of a 5-day smoothing interval is appropriate given the 5-day duration of the traffic restrictions. Figure 4 presents time series for emissions corresponding to three spatial scales: 0.5° × 0.5°, 1° × 1°, and 2° × 2.5°.

[11] Highest emissions (emissions per unit area per unit time) were obtained using the highest resolution averaging procedure (0.5° × 0.5°), indicating that emissions from the Beijing urban area are higher than those from the immediate surrounding region. Emission fluxes over the Beijing urban area (0.5° × 0.5°) were reduced by up to 40% during the period when strict traffic restrictions (4 Nov to 6 Nov) went into force. The analysis suggests that the emissions over an extended area of 1° × 1° around Beijing were reduced also by 40% during the period of traffic restrictions. No significant changes in emissions were detected when the data were averaged to the 2° × 2.5° scale. Since traffic restrictions were imposed primarily in the Beijing urban area, the similarity in results obtained with resolutions of 0.5° × 0.5° and 1° × 1° would appear to imply that emissions from the urban area were transported horizontally occupying the 1° × 1° grid and dominate all other sources on that scale. Since the impact of the traffic restrictions is not detectable on the 2° × 2.5° scale, we conclude that emissions from Beijing are significantly diluted on this scale by regional sources.

[12] Since the present study is focused mainly on the ***relative*** changes in emissions during the traffic restriction, systematic errors associated with the OMI data and the model simulation and systematic mismatches between the two data sources are not expected to influence significantly conclusions drawn from the present analysis. Errors thus come mainly from random errors of OMI and the model. The standard deviation of daily emissions (prior to smoothing) during the period of normal levels of emissions (i.e., excluding 4–6 November) is adopted as a proxy to represent the random errors in the system. This method gives an estimate of 25% uncertainty, significantly lower than the 40% reduction in emissions inferred for the period of traffic restrictions.

4. Concluding Remarks

[13] We conclude that traffic restrictions implemented during the Sino-African Summit were remarkably successful in reducing emissions of NO_x – by as much as 40%. Recent analysis of extremely high ozone events in Beijing urban plumes in summer showed strong positive linear correlations between O_3 and total reactive nitrogen [*Wang et al.*, 2006]. Given the important role of NO_x in the formation of O_3, our analysis suggests that traffic restrictions could be effective also in controlling O_3 pollution by reducing emissions of both NO_x and VOCs from vehicles.

[14] The bottom-up method estimates that vehicular emissions contributes about 70% of NO_x sources over the Beijing urban area during non-heating seasons (the official winter heating period in Beijing starts in late November) (Q. Zhang and D. Chen, personal communication, 2007). If we adopt this number and assume further that there were no changes in non-mobile sources during the Summit, the present study would indicate that traffic restrictions reduced vehicular emissions of NO_x by about 50%. This number appears to be higher than the fractional change in on-road vehicle numbers reported in the news media. Detailed data on vehicle energy usage (e.g., gasoline sales data) will be required to develop a more precise value for the relative reduction in vehicular emissions.

[15] Temporal variations in NO_2 over the period October 25 to November 19 are accurately captured by the GEOS-Chem model employed in this analysis. The model assumed an inventory of emissions available for 2004. Absolute values of NO_2 column densities obtained with the model were typically lower than observed columns, by about 30%. This discrepancy may be due at least in part to the increase in emissions that has occurred since 2004: new car registrations are growing at present by about 15% annually. It is anticipated that restrictions similar to those implemented during the Sino-African Summit will be instituted in the future as Beijing prepares to host the 2008 Olympic Games. OMI NO_2 data can be used in the NRT mode to check if such measures are indeed effective. Coordinated observations of multiple species on such occasions can provide invaluable opportunities to test and refine our understanding

of atmospheric chemistry not only for Beijing but also for the large region of East Asia.

[16] **Acknowledgments.** OMI NRT data were provided by KNMI (The Netherlands) and were produced in collaboration with NASA (USA). OMI, a Dutch-Finnish built instrument, is a part of NASA's EOS-Aura payload. The OMI project is managed by NIVR and KNMI in The Netherlands. Y. X. Wang thanks Shuxiao Wang, Weihua Ge, Dan Chen at Tsinghua University, and Qiang Zhang at Argonne National Laboratory for helpful discussions. This research was supported by the National Science Foundation, grant ATM-0635548.

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