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Change of NO_2 column density over Beijing from satellite measurement during the Beijing 2008 Olympic Games

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The effect of the air quality ensuring measures for the Beijing 2008 Olympic Games in reducing air pollution during the game period is assessed using the tropospheric NO_2 column density retrieved from Ozone Monitoring Instrument onboard AURA satellite. The basic method of the assessment is the comparison of the NO_2 column densities during the game period with that during the corresponding period of 2005—2007 for the Beijing area, and the comparison among Beijing and neighbouring cities Tianjin and Tangshan, which are of similar situation in air pollution of NO_2 in recent years. The images of tropospheric NO_2 column densities over Northern China during the Beijing 2008 Olympic Games show the remarkable effect of the air quality ensuring measures in reducing NO_2 pollution: the tropospheric NO_2 column density in Beijing is much lower than that in Tianjin and Tangshan, while there were very similar values in the three large cities during the same period of the last three years. About 40% reduction in tropospheric NO_2 column density over the Beijing area is obtained from the assessment during July to August, 2008, a key period of air quality ensuring measures for the Beijing 2008 Olympic Games.

Beijing 2008 Olympic Games, air quality ensuring measures, effect assessment, OMI, NO_2

Nitrogen oxides including NO and NO_2 play very important roles in atmospheric chemical processes in the troposphere. NO_x takes part in the photochemical reaction of producing ozone, resulting in the augmentation of ozone concentration in the lower atmosphere and photochemical smog, which is toxic to human health, and their transformation to acid rain are harmful to humans, animals, agriculture and many cultural relics.

The main emission sources of NO_x are fossil fuel combustion, soil release, biomass burning and lightning[1]. Anthropogenic activities should be responsible for the most of the emissions[2,3]. Of the anthropogenic emissions, most are from fast increasing vehicles, power plants and other factories. The vehicular emission may account for about 70% of NO_x sources in the total over Beijing urban areas during all seasons but heating season (mid-November to mid-March)[4]. As the fastest developing country, China has the most rapidly increasing NO_x emission, much faster than other developing countries, which is closely associated to the fast increasing number of vehicles in China[2,5−7].

Since 1990, the application of satellite remote sensing has been extended to many fields of the environment protection. Compared with ground-based measurement, satellite observation has the advantages of large coverage, near real time and high resolution. It can help ob-

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tain some important parameters in spatiotemporal distribution, which can be used to predict the long-term trends of some important trace gases. However, it is hard to be accomplished by the current routine ground-based observation. Many achievements have been obtained since 1996 by several satellite sensors for the global distribution of tropospheric NO_2 vertical column density (VCD)[4,8,9].

Beijing, as the political, economic and cultural centre, is one of the megacities in the world because of its fast economic and social development. However, the development results in extending construction zones, augmenting population, and increasing vehicles, causing large emission of air pollutants and serious situation in air pollution. "Green Olympic Games, Scientific and Technological Olympic Games and Humanistic Olympic Games" were proclaimed to be three themes for the Beijing 2008 Olympic Games when China bid for the games. However, Green Olympic Games was put in first place. In order to well implement the promises given in the application for the Olympic Games, to provide successful, unique and high level Olympic Games through further improving air quality, six measures were authorized by Beijing municipality and were carried out during the period of the Beijing 2008 Olympic Games and Paralympics such as traffic restriction, strictly control to the key construction, emission reduction of the key enterprises in air pollution being tracked, etc. The measures on vehicles inside Beijing and the vehicles of neighboring provinces to Beijing started from July 1, 2008. Before the opening of the Beijing 2008 Olympic Games, there were 3.4 million of vehicles in Beijing according to the information provided by the Beijing Municipal Environmental Protection Bureau. About 60% vehicles in Beijing (approximately 2 million) were taken off the roads during the period of the Olympic Games due to the traffic restriction measure.

The air quality ensuring measures for the Beijing 2008 Olympic Games were carried out with several phases. Starting from June 23, 2008, about 50% of vehicles of governmental institutions and enterprises were restricted, and the restricted vehicles increased to 70% after July 1. At the same time, those high emission vehicles classified to yellow mark vehicles which failed to meet European emission standard No.1 were restricted on roads, and the trucks for cargo registered outside Beijing without special permits were prohibited to drive on roads inside Beijing. They must detour using roads of Hebei Province to avoid passing through Beijing. The "odd days for odd number cars and even days for even number cars" regulation was carried out since July 20. Many high emission power plants using coal and other factories in Beijing and surrounding regions were forced to work under the given limited emission amount, otherwise will be shutdown. Some enterprises were required to reduce their productivity or stop production. All air quality ensuring measures ended on September 20, 2008, when the Paralympics finished. According to the measurement results from Beijing EPB and the investigation from Chinese Research Academy of Environmental Sciences and Beijing University of Technology, the high emission factories in Beijing can meet the guideline of emission quantity required by Beijing municipal government. However, the emissions of the enterprises situated in the surrounding regions did not well meet the guideline of emission quantity until the Olympic Games approached. These enterprises reached the guideline gradually.

The ozone monitoring instrument (OMI) onboard AURA satellite of the earth observation system (EOS) provides high quality data of the regional distribution of tropospheric NO_2 VCD. Here the effect of improving air quality of the air quality ensuring measures for the Beijing 2008 Olympic Games is assessed by comparing the NO_2 column density data during the Olympic Games in Beijing with that during the same period of 2005－2007 in the same city, and also with neighboring large cities, Tianjin and Tangshan, looking for the changes and the differences.

1 OMI instrument and the retrieval approach of NO_2 VCD

The Dutch-Finnish OMI on NASA's EOS Aura satellite is a nadir-viewing image spectrograph measuring direct and atmosphere-backscattered sunlight in the ultraviolet-visible (UV-VIS). Aura satellite was launched on 15 July, 2004. It is in a near-polar, Sun-synchronous orbit at approximately 705 km with a 13:40－13:50 local time equator crossing time. OMI uses 2-dimension charge-coupled device (CCD) detector to measure solar spectra of ultraviolet and visible range from 270 nm to 500 nm. OMI has 2600 km swath on the Earth's surface, large enough to achieve complete global coverage in one day. OMI's spatial resolution is 24 km×13 km at nadir, and it becomes lower in off-nadir direction, being approxi-

mately 128 km×13 km at edge views with 57° viewing angles[10,11].

The near-real time retrieval algorithm of tropospheric NO_2 VCD from OMI measurement is based on the combined retrieval-assimilation-modeling (RAM) approach developed at the Royal Netherlands Meteorological Institute (KNMI)[10]. NO_2 slant column densities are retrieved by means of spectral fitting to direct solar spectra and the earth reflecting solar spectra, which is so-called Differential Optical Absorption Spectroscopy (DOAS) method. The spectral fitting is made in the range of 405 nm to 465 nm, which is dominated by the absorption of NO_2. In the current version, the approach accounts for absorption by ozone and the Ring effect due to rotational Raman scattering. This approach requires nonlinear fitting unlike the traditional DOAS. Online availability of stratospheric slant columns and NO_2 profiles are achieved by running the TM4 chemistry transport model forward in time based on forecast of ECWMF meteorological field and assimilated NO_2 information from all previously observed orbits. Tropospheric AMF is computed with a radiative transfer model depending on NO_2 profile, cloud fraction, cloud height, surface albedo, and view geometry. Compared with NASA's NO_2 standard algorithm[12], it has advantages of faster data processing and smaller errors. It takes about 3.7 h to finish data transfer and their processing and image generation after the data sampling by satellite instrument, while it needs one whole day for NASA's standard algorithm[10].

An individual OMI tropospheric NO_2 VCD retrieval error is composed of that from slant column that is estimated at $\pm0.5\times10^{15}$—$\pm1.5\times10^{15}$ mol/cm^2 and a relative uncertainty of 10%—40% from the AMF calculation[10,13].

OMI's tropospheric NO_2 VCD dataset has been widely used to analyze the change trend of the NO_2, global distribution, monitoring of important atmospheric environment events and their effects to ecological environment, economy and society[4,6,7].

2 Change of Tropospheric NO_2 VCD during the Beijing Olympic Games

The OMI product will be applied to evaluating the reduction of NO_x emission due to the air quality ensuring measures for the Beijing 2008 Olympic Games. First, averaged summer (June, July and August) tropospheric NO_2 VCDs (2005—2007) derived from OMI over northern China are presented in Figure 1. Then the tropospheric NO_2 VCDs in Beijing during the Olympic Games are compared with those of the same period of 2005—2007 and those of neighbouring cities, Tianjin and Tangshan.

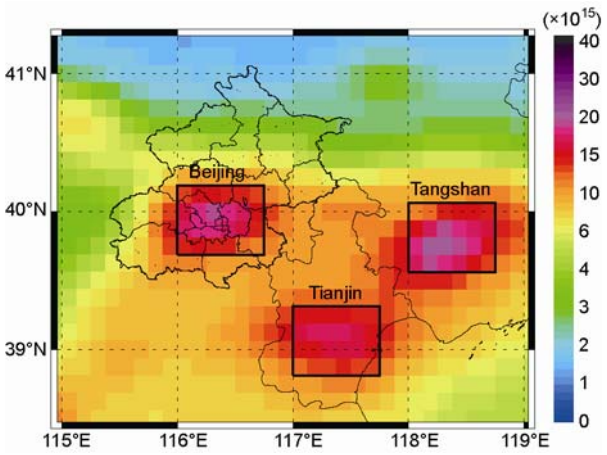

Figure 1 The tropospheric NO_2 vertical column densities averaged during the summer (June—August) of 2005—2007 over Beijing, Tianjin and Tangshan areas, in unit mol/cm^2. The three areas marked by the black frames are centered at (116.38°E, 39.94°N), (117.38°E, 39.06°N), (118.38°E, 39.81°N) with the size of 0.75°× 0.5°, represent the polluted areas over Beijing, Tianjin and Tangshan. The averaged densities over the three marked typical areas in the figure are almost the same, around 15×10^{15} mol/cm^2.

Figure 1 shows summer averaged tropospheric NO_2 VCD (2005—2007) derived from OMI over Beijing areas. The pixels of radiance equivalent cloud fractions exceeding 50% were excluded from the present analysis in order to guarantee data quality. The available samples account for about 40% in all statistical days. Three high NO_2 pollution areas with almost the same size centering at Beijing, Tianjin and Tangshan are shown in the figure. The NO_2 concentration decreases toward the rural areas from the urban centers because of the short life time of NO_2, which is only several hours in summer. Therefore, NO_2 cannot transport far away. Beijing, Tianjin and Tangshan cities are megacities with a large of population or a developed industrial area. The areas centered at (116.38°E, 39.94°N), (117.38°E, 39.06°N), and (118.38°E, 39.81°N) with the size of 0.75°(Long.) × 0.5° (Lat.) represent the three air polluted areas in Beijing, Tianjin and Tangshan, respectively. The OMI NO_2 data over the three areas are used to analyze the change of NO_2. The area in Beijing represents approximately the urban area of about 2000 km^2. This area size can well represent high NO_2 density areas, and include enough satellite image pixels to reduce statistical errors.

The tropospheric NO_2 VCD data retrieved from OMI in northern China during the Beijing 2008 Olympic Games and the past three years are employed to assess the effect of the air quality ensuring measures. Figure 2 shows the daily variation of tropospheric NO_2 VCD over Beijing, Tianjin and Tangshan during June to August, 2008. It can be seen that there was relatively high NO_2 VCD in June over Beijing with large fluctuation, sometimes exceeding 20×10^{15} mol/cm^2. The density even reached 47×10^{15} mol/cm^2 and 36×10^{15} mol/cm^2 in June 5 and June 12. Unfortunately, most data in late June was not available because of rainy days. Since the beginning of July, NO_2 VCD remained at lower values, around 5×10^{15}—15×10^{15} mol/cm^2. The tropospheric NO_2 VCDs over Tianjin and Tangshan were more fluctuated, generally larger than that in Beijing since the beginning of July, but it had been opposite in June. The tropospheric NO_2 VCD in summer is dominated by the emissions of NO_x and the meteorological conditions, which affect the NO_x lifetime and its horizontal divergence. Here the contribution of long-range transport is ignored because of NO_x short life of hours in summer. Because of the air quality ensuring measures such as traffic restrictions, shutdown or quota-limited production and standard-meeting emissions for the high emission factories in Beijing and its surrounding regions, the NO_2 VCDs over Beijing have been much lower than those over Tianjin and Tangshan since early July. Furthermore, they are much lower than those in June when compared with that over the same area. These facts strongly show that the air quality ensuring measures during the Beijing 2008 Olympic Games were remarkably successful in reducing the tropospheric NO_2 VCD.

In order to filter the effect of weather conditions, and to compare with the same period of 2005—2007, 10-day averaged tropospheric NO_2 VCD during the period of the Beijing 2008 Olympic Games is employed as shown in Figure 3. At early and middle June, the averaged tropospheric NO_2 VCD in Beijing was greater than that in Tianjin and Tangshan, while after the implementation of key air quality ensuring measures, the averaged density went down, remarkably lower than those in Tianjin and Tangshan by 5×10^{15}—10×10^{15} mol/cm^2. This is very different from the situation in 2005—2007, when the averaged values in Tangshan was a little higher than in Beijing and Tianjin but was approximately the same in July and August. This implies that there would be similar situations of air pollution in Beijing, Tianjin and Tangshan cities without the air quality ensuring measures. The sharp decrease of NO_2 appears at early July, coinciding with the time of the prohibition of high emission yellow marked vehicles. This may imply that the prohibition of high emission yellow marked vehicles can remarkably reduce the emission of air pollutants. At the time of the Olympic Games, the yellow marked vehicles were recorded to over 300000. Since a vehicle of yellow mark emits air pollutants as many times as an emission-qualified vehicle, yellow mark vehicles as a sum contribute a large fraction to total emission of all vehicles. It requires further study to obtain accurate number of the fraction. By comparing the change of tropospheric NO_2 VCD between July 1 to 20 and July 21 to August

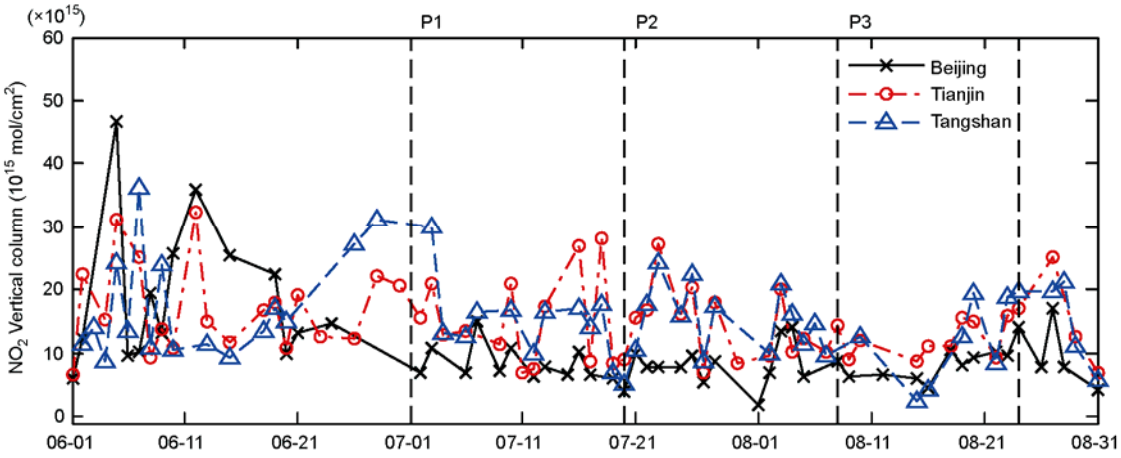

Figure 2 The daily variation of the tropospheric NO_2 vertical column densities during the summer (June—August) in 2008 over Beijing areas. The cross signs, red circles and blue triangles are for Beijing, Tianjin and Tangshan, respectively. P1 means the phase 1, starting the prohibition of high emission vehicles since July 1. P2 starting the alternatively using roads by the vehicles of odd and even numbers. P3 for the Beijing 2008 Olympic Games from August 8 to 24. All the air quality ensuring measures ended at September 20, 2008, when the Paralympics finished.

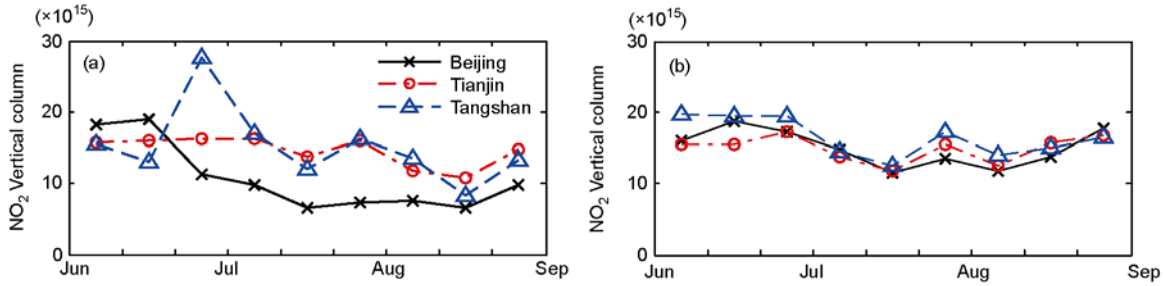

Figure 3 The variation of 10-day averaged tropospheric NO_2 vertical column densities during June to August for 2008 (a) and for 2005—2007 (b). The black cross signs, red circles, and blue triangles represent the density over Beijing, Tianjin and Tangshan, respectively (unit: 10^{15}mol/cm^2).

31, it can be seen that the decrease in NO_2 is smaller in the latter period than in the former one. This implies that prohibiting the high emission vehicles is much more effective than prohibiting emission-qualified vehicles in reducing the emission of air pollutants.

Figure 4(a) represents the regional distribution of the averaged NO_2 VCD around the period of the Olympic Games from July to August of 2008 over Beijing, Tianjin and Tangshan. Comparing to the image of the distribution for the same period of 2005—2007 (Figure 4(b)), the remarkable difference can be found during the Beijing 2008 Olympic Games between Beijing and the neighboring large cities, while the three cities have very similar air pollution situation during the same period of recent three years. From July to August, 2008, the maximum values over Beijing area were much lower than those in Tianjin and Tangshan. The tropospheric NO_2 VCDs were below 10×10^{15} mol/cm^2, while they were between 15×10^{15}—20×10^{15} mol/cm^2 over Tianjin and Tangshan areas. However, the tropospheric NO_2 VCDs were all above 15×10^{15} mol/cm^2 during the same period of 2005—2007. Overall, the tropospheric NO_2 VCDs were lower in 2008 than in 2005—2007 over Tianjin as well as over Tangshan. This implies that the ensuring measures such as the shutdown or quota-controlling production of the key high emission factories took certain effect in air pollutants reduction. In fact, similar traffic restriction measures were carried out during the Beijing 2008 Olympic Games in Tianjin urban areas inside the ring roads for a shorter period than in Beijing. However, the effect in reducing air pollutants was less remarkable over Tianjin and Tangshan than over Beijing area. This is consistent with the fact that the ensuring measures were less in strength, shorter in time period, smaller in area, and less strict in Tianjin and Tangshan than in Beijing.

3 Quantitative assessment of the reduction of NO_2 column density

Table 1 gives the averaged NO_2 VCD during the periods of June, July to August in 2008 and 2005—2007 over

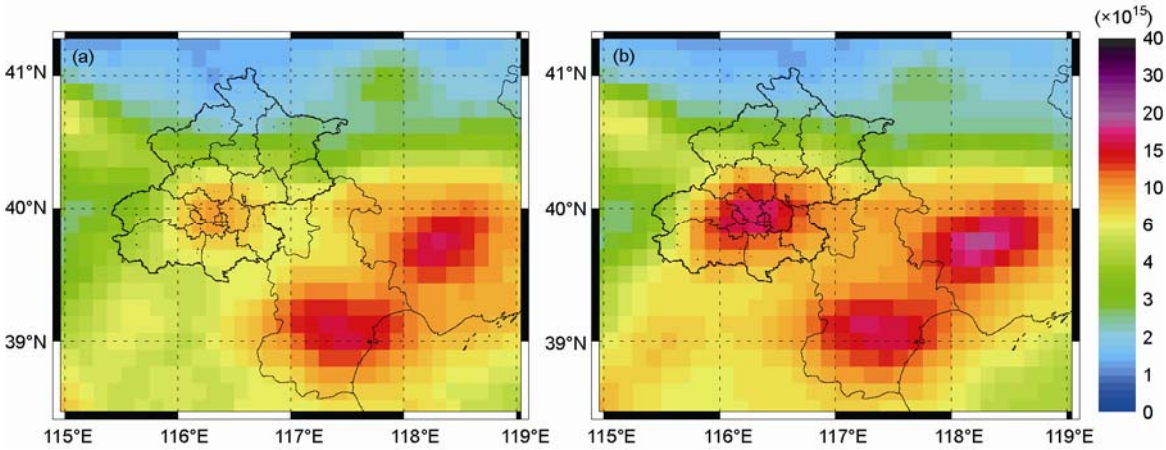

Figure 4 The averaged tropospheric NO_2 vertical column densities over Beijing during July to August for 2008 (a) and for 2005—2007 (b) (unit: mol/cm^2).

Table 1 Tropospheric NO_2 VCD for Beijing in summer (unit: 10^{15} mol/cm^2)

	2008		2005－2007	
	Jun	Jul－Aug	Jun	Jul－Aug
Beijing	16.2	7.9	17.4	13.9
Tianjin	16	13.8	16.1	14.4
Tangshan	18.7	13.4	19.6	15.0

Table 2 The change of tropospheric NO_2 VCD during summer over Beijing

	Jul—Aug 2008 vs. Jul—Aug 2005—2007	Jul—Aug vs. Jun of 2008	Jul. —Aug. vs. Jun. of 2005—2007
Beijing	–43.2%	–51.2%	–20.1%
Tianjin	–4.2%	–13.8%	–10.6%
Tangshan	–10.7%	–28.3%	–23.5%

Beijing, Tianjin and Tangshan. It can be found that there was little difference in tropospheric NO_2 VCD among Beijing, Tianjin and Tangshan during the periods without air quality ensuring measures such as July－August of 2005－2007 and June of 2008, because of the similar weather conditions for the three areas. The tropospheric NO_2 VCDs vary between 16.2×10^{15}－18.7×10^{15} mol/cm^2. Particularly, the densities are almost the same in Beijing and Tianjin. While during the period of air quality ensuring measures in July to August of 2008, the tropospheric NO_2 VCD went downward to 7.6×10^{15} mol/cm^2, only the half of the value of 2005－2007. However, there were no large difference for Tianjin and Tangshan, just slightly lower in 2008 than in earlier years. This fact indicates that the implementation of the air quality ensuring measures remarkably improve the air quality during the Olympic Games, and it strongly guarantees the proceedings of the Beijing 2008 Olympic Games in good air quality.

The comparisons of the tropospheric NO_2 VCDs among Beijing, Tianjin and Tangshan cities for the periods of the Olympic Games and the same period of 2005－2007 are given in Table 2. Three kinds of comparisons are carried out here. First, by the comparison of NO_2 of July to August of 2008 with those of the same period of 2005－2007, it can be found that the tropospheric NO_2 VCDs decreased in all cities of Beijing, Tianjin and Tangshan, in which 43.2% reduction could be seen in Beijing, and small reduction of 4.2% and 10.7% for Tianjin and Tangshan, respectively. Second, when comparing the NO_2 densities during July to August of 2008 with those of June of the same year, the large reduction can also be found, reaching 51.2%, much greater than 13.8% and 28.3% in Tianjin and Tangshan, respectively. Third, in order to study the relationship between the tropospheric NO_2 VCDs and the air quality ensuring measures more carefully, the NO_2 density during June of 2005－2007 and that during July to August of the same year were compared. It is found that there was only a decrease of 20.1% in Beijing, but 10.6% and 23.5% in Tianjin and Tangshan respectively. These values are some lower than those in 2008.

As we know, the tropospheric NO_2 density is dominated mainly by three factors, which are emission source of NO_x, its life time and regional transportation. According to the weather records in the summer of many years, the changes of weather systems in the northern China are dominated by the cycle of 5－7 days. Therefore, we take the 10-day average for filtering as much as possible the influences of weather processes in order to clearly show the relationship between the NO_2 VCD and the air quality ensuring measures for the Olympic Games. In order to obtain more accurate results of the air quality ensuring measures for the Olympic Games the annual variation of NO_x emission is investigated here. The annual variation is represented by the averaged NO_2 density of January to June, because the NO_2 density was not affected by any air quality ensuring measures whether in 2005－2007 or in 2008. Considering January to June, the averaged tropospheric NO_2 VCD in Beijing was 24.9×10^{15} mol/cm^2 and 24.8×10^{15} mol/cm^2 for 2008 and 2005－2007, respectively, showing nearly no difference. This indicates that there were no differences in Beijing in the averaged emission intensity during the recent four years before the Olympic Games. Therefore, we obtain 43.2% reduction in NO_2 column density since the implementation of the air quality ensuring measures on July 1, 2008. These results are obtained in comparison with the same period of July to August between 2008 and 2005－2007, which can be considered as the effect in emission reduction due to the air quality ensuring measures. While using the same method, we obtain 18.1% and 19.6% in Tianjin and Tangshan during the same period of July to August of 2008.

Another method to assess the effect in emission reduction due to the air quality ensuring measures is tried here. The NO_2 column density during July to August of 2008 with the ensuring measures and that during June of the same year is compared. In this way, rather than considering the annual change trend of emission, we only

need to take into account the seasonal variation of NO_2 column density. When setting the monthly averaged NO_2 during 2005—2007 as the baseline, the value of July to August of 2008 without the air quality ensuring measures for the Olympic Games should be calculated as

$$NO_2^*[\text{Jul—Aug 2008}] = NO_2[\text{Jun 2008}] \cdot \frac{NO_2[\text{Jul—Aug 2005—2007}]}{NO_2[\text{Jun 2005—2007}]}.$$

Then comparing the NO_2 column density observed with the ensuring measures and the density without those, we obtain the decreases by 38.9%, 3.6%, and 6.3% in the column density during July to August of 2008 in Beijing, Tianjin, and Tangshan, respectively. The values given by this method should be more reliable than that given by the former method because the annual change trend of emission intensity can be filtered out.

4 Conclusions

The tropospheric NO_2 vertical column density data retrieved from the OMI instrument aboard AURA satellite are applied to assess the effect in emission reduction of the air quality ensuring measures for the Beijing 2008 Olympic Games. First, the NO_2 column densities in Beijing during the ensuring measures in 2008 are compared with those of the same period of 2005—2007. Second, they are compared with those in Tianjin and Tangshan, the neighboring cities, in which there were similar situation in air pollution. According to the analysis of the change and the regional distribution of the column density with and without the air quality ensuring measures, it can be concluded as the following:

(i) The images of the tropospheric NO_2 VCD in north of China show that there are three polluted areas with high NO_2 column density, including Beijing, Tianjin and Tangshan city. There are similarly high values that are between 14×10^{15}—15×10^{15} mol/cm^2 in the three large cities during the same period of the last three years.

(ii) The tropospheric NO_2 VCD in Beijing is much lower than in the neighboring cities, Tianjin and Tangshan, during the Beijing 2008 Olympic Games due to the strict air quality ensuring measures, while there were very similar values in these three cities in last three years.

(iii) There is about 40% reduction in tropospheric NO_2 VCD in Beijing region during the Beijing 2008 Olympic Games due to the air quality ensuring measures. Tropospheric NO_2 VCD data in Beijing area over the period of June to August of 2005—2008 are used to assess the effect of the measures. By filtering as much as possible the influences of weather conditions on changes of emission sources, 43.2% and 38.9% reduction in tropospheric NO_2 VCD in Beijing by two effect assessment methods are obtained.

OMI NRT data were provided by KNMI (Netherlands) at www.temis.nl.

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