Formation and causes of NO_x pollution on the east side of the Taihang Mountains in China

TIAN HeZhong^{1*}, WANG Yan¹, ZHAO Dan¹, CHAI FaHe², XING ZiShan³ & CHENG Ke¹

¹ State Key Joint Laboratory of Environmental Simulation & Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, China;

² Chinese Research Academy of Environmental Sciences, Beijing 100012, China;

³ School of Computer Science and Technology, Beijing University of Posts and Telecommunications, Beijing 100876, China

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Tropospheric column amounts of NO₂ from OMI/Aura products were applied to investigate the seasonal variation of NO_x on the east side of the Taihang Mountains (ESTM) in China. The NO₂ concentration varied seasonally, with winter maxima and summer minima. To explore the causes of the heavy NO₂ pollution in this region, wind field simulations were conducted by using the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5). MM5 simulations showed that wind directions in the ESTM region were dominated by northeasterly and northwesterly winds throughout the year and to a lesser degree by southwesterlies. Elevated NO₂ concentrations (higher than 50×10¹⁵ molec/cm²) occurred in three meteorological situations: convergent wind fields (5 days), northeasterly winds (2 days), and calm days (1 day) in January. Although the local anthropogenic NO_x emission strength was not so high as that in other developed areas, the calms and frequent occurrence of convergent wind fields, as well as unfavorable terrains for diffusion, resulted in the accumulation of atmospheric pollutants and hence heavy NO_x pollution. Furthermore, long-distance NO_x transportation from the Beijing-Tianjin-Tangshan region to the ESTM area could be seen when the wind was from a northeasterly direction, especially under high wind speeds.

east side of the Taihang Mountains (ESTM), remote sensing of air pollution, satellite data, tropospheric NO₂, pollution, wind field, China

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With rapid increases in the consumption of energy, primarily from coal, rising numbers of vehicles and increasing miles driven, the primary and secondary atmospheric pollution problems associated with NO_x in China have been of increasing interest in recent years [1–4]. Heavy NO_x pollution in high-speed economic development areas, such as the Yangtze River delta (YRD) region, the Pearl River delta (PRD) region, and the Beijing-Tianjin-Tangshan region have generated extensive social concern and a national research focus on the problem [5–8]. However, we found that the east side of the Taihang Mountains (ESTM) is now a heavily NO_x polluted area as well. Although the local an-

thropogenic NO_x emission strength is not so high as that in other developed areas [9], the atmospheric concentration of NO₂ remains high in this inter-province region. Therefore, controlling NO_x emissions and pollution in the area will be listed as the priority of the 12th Five Year Plan, 2011–2015, for national environmental protection in China. Therefore, it is timely to explore the causes of heavy NO_x pollution in these areas, as well as propose effective countermeasures. In this study, we investigated the seasonal variation of NO_x pollution in the ESTM region by using NO₂ total column data retrieved from OMI/Aura (2007). Furthermore, based on the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) version 3.7, we conducted meteorological numerical simulations to explore the possible formation causes

*Corresponding author (email: hztian@bnu.edu.cn)

of high NO₂ concentration in the ESTM region.

1 Method and data

1.1 NO₂ measurements from OMI satellite

The OMI (Ozone Monitoring Instrument) aboard the EOS AURA satellite is an UV/VIS nadir solar backscatter spectrometer. The Aura satellite, launched in July 2004, crosses the equator at approximately 13:45 local time. The OMI has global atmospheric coverage and high spatial resolution (24 km×13 km). The OMI is characterized by its low signal noise ratio compared with other instruments. The basic algorithm for the retrieval of total column and tropospheric NO₂ is described by Boersma et al. [10].

Here, we use tropospheric column amounts of NO₂ from the DOMINO (Dutch OMI NO₂) product v1.02, and we grid the product into a horizontal resolution of 0.5° latitude by 0.5° longitude. NO₂ is usually treated as representative of NO_x. Owing to the high spatial and temporal coverage, OMI satellite measurements have been widely used in the monitoring of NO_x concentrations and trends [6,11,12], evaluation of control measures [13,14], as well as assessing NO_x emissions inventories [15]. NO_x in the lower troposphere is derived primarily from emissions at the surface [16]. The OMI NO₂ columns discriminate differences in ground NO₂ and the results well reflect the distribution of surface NO₂ concentrations [17,18].

To verify the reliability and validity of the OMI measurements, the retrieved OMI NO₂ columns have been compared with ground-based remote sensing measurements [19,20], aircraft measurements [21,22], as well as ground-based *in-situ* NO₂ measurements [18,23–25]. These findings suggest that the OMI NO₂ columns are suitable for regional air quality studies.

1.2 Meteorological model

The MM5 configurations adopted in this study are illustrated in Table 1. The MM5 simulations were conducted from January to December 2007, corresponding with OMI measurements. The simulations were run continuously for each month. The first domain consists of 55 × 48 grids with a resolution of 81 km × 81 km and covers most of the areas of China as well as the Korean Peninsula and Japan. The second nested domain consists of 79 × 61 grids with a resolution of 27 km × 27 km and covers the entire area of central and eastern China. The third nested domain consists of 79 × 82 grids with a resolution of 9 km× 9 km and covers the whole areas in and around the Beijing-Tianjin-Tangshan Region, and the ESTM. The vertical resolution includes 23 layers. The 6 hourly NCEP FNL Operational Global Analysis data are from the Computational and Information Systems Laboratory (CISL, <http://dss.ucar.edu/datazone/dsszone/ds083.2/index.html?g=1>) at the National Center for Atmos-

Table 1 MM5 configurations

Parameters	Settings
Period	January–December, 2007
Output	Interval 1 h
Central point	33.8°N, 115°E
Horizontal grid	55 × 48 (81 km grid size) 79 × 61 (27 km grid size) 79 × 82 (9 km grid size)
Vertical grid	23 layers
Terrain data	30" resolution USGS data
Land-use data	25 category with 30" resolution USGS data
Objective analysis data	NCEP FNL Operational Global Analysis data
Cumulus scheme	Grell
Explicit moisture scheme	Simple ice
Atmospheric radiation scheme	Cloud
Planetary boundary layer scheme	MRF
Surface scheme	Five-layer soil model
Nesting	Two-way nesting

pheric Research (NCAR). These are on 1.0°×1.0° grids continuously at a 6-h intervals.

2 Seasonal variation of NO_x pollution in the ESTM region

Seasons were defined as: spring, March to May; summer, June to August; autumn, September to November, and winter: from December to February. The overall average concentration of NO₂ for 2007 was divided into eight grades and plotted onto a 0.5° × 0.5° grid (Figure 1).

NO_x emissions in China are distributed very unevenly because of the great difference in economic activity, energy consumption, degree of development, as well as density of population throughout the country [26]. NO_x emissions have been mainly concentrated around the populated and industrial centers of China—largely the coastal provinces in the eastern and the southern areas, such as Shandong, Guangdong, Zhejiang and Jiangsu. In general, there were four regions emitting large amounts of NO_x in China: the YRD, the PRD, the Beijing-Tianjin-Tangshan region, and the Sichuan Basin (Figure 2) [9].

However, the five regions where the concentrations of NO₂ were relatively high can be divided into two types: (1) those with heavy emissions and high concentrations, including the YRD, the PRD, the Beijing-Tianjin-Tangshan region, and the Sichuan Basin, and (2) those with relatively low emission strengths but high NO₂ concentrations. These include the ESTM region, which now seems to have the highest NO₂ concentrations in China. This heavily polluted region covers the intersections of the provinces of Hebei, Shanxi, and Henan.

The seasonal variation of NO_x can be influenced by a number of factors including seasonal changes in emission

Figure 1 Averaged daily OMI NO₂ tropospheric columns in four seasons, 2007 (units: 10^{15} molec/cm²).

Figure 2 The distribution of NO_x emissions in China, 2006 (cited from Zhang et al., [9]).

strengths, NO_x lifetime in the atmosphere and atmospheric circulation. Figure 1 shows the seasonal variation of OMI NO₂ tropospheric columns. The lowest concentrations of NO₂ occurred in the summer. This is consistent with the strongest vertical mixing and highest photochemical and wet-dry removal of NO₂. The highest level of NO₂ was found in winter. This pattern is consistent with that in other provinces in southern China, where the seasonal variation in OMI NO₂ columns is primarily driven by seasonal variation in the NO_x loss rate. However, in the ESTM the seasonal changes in NO₂ are probably aggravated by elevated NO_x emissions from coal burning for commercial and domestic heating.

There are of course other factors, including terrain and wind direction, that lead to high NO₂ concentrations [27,28]. The emphasis of this work, however, is to explore causes on the formation side, rather than the loss side of the NO₂ problem in the ESTM.

3 Possible causes of heavy NO_x pollution in ESTM region

3.1 Adverse terrain conditions

We used MM5 to simulate and export the daily meteorological field, and then examined the monthly variation of local atmospheric circulation in detail. Figure 3 shows the circulation field at ground level in the representative month of each season (January, April, July, and October) in 2007. It is clear that the high Taihang Mountains to the west effectively block air mass movement such that eastern areas in their lee have consistently wind speeds throughout the year. This situation is not favorable for the dispersion of atmospheric pollutants.

3.2 Wind direction

Table 2 shows the seasonal characteristics of the ground atmospheric circulation field in the ESTM in 2007. In this region, the wind was dominated by northeasterlies and northwesterlies throughout the year, with fewer southwesterly winds. Because of the terrain, westerly winds were rare. In 2007, calms (situations when wind speeds were less than 1 m s^{-1} and there was no overall or prevailing wind direction) occurred on 34 days and most of them were in autumn and winter. Calm conditions allow atmospheric pollutants to accumulate more easily, and hence aggravate air quality.

Moreover, a particular type of local meteorological flow (called “convergent” in this work), characterized by low winds and a pseudo-anticyclonic condition (Figure 4), was commonly seen in spring and winter (Table 2). This

Figure 3 Ground circulation field in the 4 representative months in ESTM region in 2007.

Table 2 Seasonal characteristics of the ground atmospheric circulation field in ESTM region

Wind direction	Time (d)			
	spring	summer	autumn	winter
NE	19	15	21	12
NW	18	9	13	26
SE	3	28	1	2
SW	24	6	12	13
E	5	12	0	1
N	3	3	10	5
S	6	7	11	7
C	2	6	15	11
Convergent	12	6	8	13

condition further aggravated local air quality, see below.

As shown in Figure 4, convergent type of wind involved two air-flows affecting the ESTM concurrently. One was a northeasterly airflow, around the north part of the ESTM, and the other was a southwesterly airflow, controlling the southern part. This pseudo “anticyclonic” condition resulted in both transportation of air pollutants from surrounding regions into this area, and reduced exchange of pollutants out of the area – effectively creating a “jar” around the area in which pollutants accumulated. Consequently, the highest NO_2 column density was observed by OMI under these

Figure 4 Convergent type of wind on the east side of the Taihang Mountains.

conditions.

To analyze how NO_2 levels varied with wind direction, we extracted the OMI tropospheric NO_2 column of each grid square in area ($114^\circ\text{--}115^\circ\text{E}$, $35^\circ\text{--}39^\circ\text{N}$), to identify in which grid squares the maximum value appeared most frequently throughout the year. This process identified 27 grid squares altogether. January was selected and analyzed as the representative month for winter.

The prevailing wind direction in winter was northwest. The MM5 simulated results showed that the wind speeds

Figure 5 Daily average OMI tropospheric NO_2 columns and wind direction for January, 2007 ($114^\circ\text{--}115^\circ\text{E}$, $35^\circ\text{--}39^\circ\text{N}$, units: 10^{15} molec/ cm^2 ; C signifies calm winds and Co signifies convergent wind).

associated with the northwesterlies were strong and favorable for the diffusion of atmospheric pollution. Figure 5 shows the daily average NO_2 concentrations were relatively low when the northwesterlies were blowing.

These results show that high NO_2 concentrations usually occurred under either calm conditions or under northeasterlies and with a convergent wind field. Clearly, these conditions were unfavorable for atmospheric diffusion and led to the accumulation of pollutants, and thus may result in the elevated high level of NO_2 concentration in the ESTM region. Moreover, the influence of NO_x transportation from the northern Beijing-Tianjin-Tangshan region to the downwind ESTM area could be seen clearly when northeasterlies were blowing, especially when wind speeds were high.

4 Conclusions

In this paper, we investigated the seasonal characteristics of NO_x pollution in ESTM region of China using OMI data and meteorological modeling with the MM5 model. Tropospheric column NO_2 measured by OMI appears to be sensitive to the changes in NO_2 concentrations at ground level. The lowest concentration of NO_2 appeared in summer and the highest level of NO_2 was found in winter. MM5 simulation and analysis showed that the high NO_2 concentrations in the ESTM can be ascribed mainly to the unfavorable terrain and the mesoscale atmospheric circulation. There are also relatively high anthropogenic emissions. The calms and frequent occurrence of a convergent wind field resulted in the accumulation of atmospheric pollutants, which aggravated air quality in the area. The influence of NO_x transportation from the Beijing-Tianjin-Tangshan region to the downwind ESTM area could also be seen clearly when northeasterlies were blowing, especially when wind speeds were high.

Our results demonstrate that OMI can be used for regional pollution studies, particularly where ground-level monitors are not available.

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