Fluctuation Characteristics of NO_2 Pollution over Yangtze River Delta during the Period of Global Financial Crisis

Yin Du and Zhiqing Xie

***Abstract*—Using the NO_2 density data from the Ozone Monitoring Instrument (OMI) and ground-based observations, the effects of industrial fluctuations due to the financial crisis on local NO_2 pollution are quantitatively assessed. The results are as follows. (1) The global financial crisis caused distinct V-shaped fluctuations from May2007 to Dec2009 and the largest anomalies of more than 1.5 times the standard deviations at the height of the crisis period of Nov2008 to Feb2009, for major industrial products, thermal generating capacity, electricity consumption, and tropospheric NO_2 densities. (2) Among all industrial sectors, the thermal power sector was mainly responsible for fluctuations in local NO_2 pollution during the crisis period. Especially, in the Yangtze River Delta, the thermal power sector has the greatest share of coal consumption, namely 65.96%. Since electricity is mainly obtained from local coal-burning thermal plants without NO_x-processing equipment, installing NO_x-removal devices for all thermal power plants is at present an important, feasible way of controlling local NO_x pollution.**

***Index Terms*—Financial crisis, structural changes with chow test, NO_x pollution, Yangtze River delta.**

I. Introduction

Increases in nitrogen oxides (NO_x) in the troposphere due to rapid economic development and industrialization have been observed by satellite and ground-based observations in recent decades over east central China, putting human health and ecosystems at risk [1]-[6]. East central China has become one of the world's most serious areas of NO_x pollution. Among China's major anthropogenic NO_x sources, i.e., the coal-burning thermal power industry, heavy industry, and road transport, the thermal power industry is the largest emitting source, accounting for 49.9% of total annual anthropogenic NO_x emissions of about 16.245 million tons and accounting for more than half of national yearly coal consumption, according to China's annual statistics report on the environment in 2008 [7]. Based on figures in the China Statistical Yearbook, 2009, about 85% of coal-burning thermal power plants have been built in east and central parts of China to meet local electricity demand, which has arisen from rapid industrialization and urbanization, and this region has the greatest concentration of NO_x emissions in the country. Road transport is the second-largest NO_x source of China. However, its NO_x emission accounts for slightly more than one-third of thermal power emissions in 2008, namely 17.4% of total NO_x emissions, according to the annual statistic report on the environment in China [7]. As a result of the increase in NO_x emissions from energy consumption and transport, the character of acid rain in China has changed from one of sulfuric acid to a mixture of sulfuric and nitric acids, the NO_3^- portion having increased from one-tenth in the 1980s to one-third in 2000s [8], [9]. The rapid increase in NO_x emissions has partially offset the progress in SO_2 emissions reduction in China, leading to exacerbation of the acid rain problem. This has prompted the Chinese government to develop a scheme to control NO_x emissions and pollution during the period of the 12th Five-Year Plan (2011–15) [10]. In an effort to reduce NO_x pollution, NO_x emissions entered the pollutants control list of the Chinese government, which has set strict controls on NO_x emissions by the thermal power industry. Therefore, it is necessary to assess quantitatively NO_x pollution from this industrial sector in China.

Recently, satellite-based observations of tropospheric NO_2 have proven useful in estimating NO_x anthropogenic emissions, making trend analyses, setting controlling measures and evaluating the skill of air quality forecast model. Using data from the Global Ozone Monitoring Experiment (GOME), Jaegle [11] identified spatial and seasonal variations in NO_x that were mainly caused by biomass burning and soil emissions over the Sahel. Satellite-retrieved summertime NO_2 column densities show large decreases in the Ohio River Valley, where power plants dominate NO_x emissions [12]. Tropospheric NO_2 measurements from the satellite instruments of GOME and the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) indicate a large growth of NO_2 densities over eastern China, one of the most polluted areas of tropospheric NO_2 in the world, especially above its industrial areas. These areas showed a rapid growth of tropospheric NO_2 densities of about 20% per year in the period 1996–2005 [2]-[4], [13]. The unique capabilities of the Ozone Monitoring Instrument (OMI) for air-quality monitoring are evident in that with its near-real-time, full global mapping and long-term continuous observations; it can observe directly the so-called weekend effect in tropospheric NO_2 variations, and it can be used to examine instantaneously the effectiveness of air-quality measures [14], [15]. For example, following large-scale restrictions in vehicular traffic in Beijing during the Sino-African Summit in 2006, reductions in associated emissions of NO_2 of about 40% were detected by OMI aboard the *Aura* satellite [16]. As a result of the effect of the air-quality control measures for the Beijing 2008 Olympic Games, a reduction in tropospheric

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NO_2 of about 40%–60% over the Beijing area and 20%–30% in surrounding cities was observed from July to August 2008, using OMI's tropospheric NO_2 column densities combined with a regional chemistry transport model [17], [18]. The accuracy of the air-quality forecast model was evaluated by comparing OMI's NO_2 data with that in a study by Herron-Thorpe [19].

Situated in eastern China, in the region of 29.0-33.5°N, 118.3-122.6°E, the Yangtze River Delta (YRD) has an area of about 108,000 square kilometers and is one of the main cultural and economic centers of China. It has undergone rapid industrialization and urbanization, having a dense population of about 78.37 million in 2008. The YRD is heavily dependent on coal to sustain its rapid economic growth. Its coal consumption, mainly from 275 local thermal power plants with 5.24 × 109 KW power-generation capacity, accounted for 14.89% of total national coal consumption in 2008, according to the China City Statistical Yearbook and Annual Statistic Report on the Environment in China. The YRD's NO_x emissions and densities have undergone rapid growth since 1996, as evident from emission inventory and satellite observations, resulting in severe local NO_x pollution [2], [4], [20]-[22]. It has been established that NO_2 in the troposphere has a relatively short lifetime, as well as a correspondingly high spatial and temporal variability; its densities exhibit a large spatial inhomogeneous distribution in the troposphere, with high densities being close to high local emissions [23]-[26]. When NO_x emissions from local industrial sources fluctuate, tropospheric NO_2 densities could give a response. The YRD experienced a significant downturn in industrial production in the first quarter of 2009 as a result of the global financial crisis: industrial output decreased by 5.7% compared with the first quarter of 2008. Local thermal generating capacity correspondingly decreased by 11.98% over the same period. Some key cities, e.g., Nanjing, Shanghai, Hangzhou, and Ningbo, which have high NO_x emissions and NO_2 densities, suffered a greater decline in industrial output of more than 10%. The global financial crisis offers an excellent opportunity to assess the effects of industrial downturn on NO_x pollution in the YRD, especially fluctuations in the thermal power industry.

In this study, we will address first the question of whether any possible changes in NO_x pollution due to the financial crisis can be detected in the existing OMI's NO_2 products in the YRD. Further, taking advantage of OMI's high spatial resolution, high quality data products and instantaneous observations, its monthly NO_2 columns products will be used to analyze spatial-temporal distribution of NO_2 pollution before and after the financial crisis and assess quantitatively the effects of thermal power-generation capacity fluctuations on local NO_2 pollution in the YRD. Finally, the necessities of changes in energy consumption and electricity generating and industrial structures will be discussed.

II. Data and Methodology

A. Date Source

1) Remote sensing data

OMI's tropospheric monthly averaged NO_2 column density data with $0.125^0 \times 0.125^0$ spatial resolutions were taken from http://www.temis.nl, provided by the Royal Netherlands Meteorological Institute (KNMI).

2) Statistical data

Monthly statistical data on thermal generation and other major industrial products were taken from the statistics bureau Web sites of major cities in the YRD.

3) Ground-based NO_2 data

Ground-based NO_2 densities, observed by environmental protection departments in the YRD, were used to assess temporal variations in ground NO_2 densities.

B. Processing the Tropospheric NO_2 Column Density Data

In KNMI's DOMINO NO_2 products, DOAS-type retrievals are very sensitive to errors in cloud parameters. The uncertainty due to cloud fraction was estimated to be up to 30% for strongly polluted regions [27]. To ensure retrieving accuracy, monthly mean tropospheric NO_2 columns from OMI in KNMI were obtained by the arithmetic average in cloud-free (cloud radiance <50%) days: pixels with a cloud radiance fraction that does not exceed 50%. As is evident in Fig. 1b, in some months over the YRD, less than 50% of the total number of days were cloud-free; but this is not the case in the referencing region (112–121°E, 34–40°N). The monthly mean NO_2 densities over these two regions show a high correlation: their correlation coefficient reached 0.95. Therefore, the uncertainty of NO_2 concentration in the YRD for the months when less than 50% of the total number of days were cloud-free can be reduced by using the data series in the referencing region.

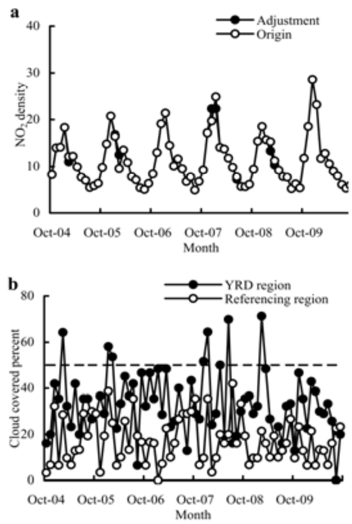

Fig. 1. Comparison of the monthly averaged NO_2 column densities before and after adjustment for YRD (a) and monthly cloud covered percents in YRD and referencing region (b).

The results are shown in Fig. 1a. A fluctuation in tropospheric NO_2 column densities is clearly evident in the OMI's DOMINO products during the financial crisis period of January 2008 to January 2010. Also in Fig. 1a, tropospheric NO_2 column densities show a stronger seasonal cycle along with the seasonal changes in air temperature. Anomaly time series were obtained from the differences between a monthly NO_2 density figure and the corresponding monthly average over several years to remove the annual cycle.

C. Methods

1) Structural abrupt analysis of time series with the chow test

Under the influence of economic fluctuations, structural changes resulting from the financial crisis could occur in the time series of industrial output value, industrial products, power generation, and pollutant densities in the YRD. Breaking points can be detected using structural changes with the Chow test. The Chow test is an established statistical approach for objectively detecting variations or structural changes in a time series. To detect quickly all breaking points, an optimal piecewise linear modeling approach with the Chow test, presented by Gao [28], was applied to find all time series with structural changes. The extension of the Chow test with the standard linear regression model is given in the following equation:

$$Y = \begin{cases} a_{10} + a_{11}t & 1 < t \le k_1 \\ a_{20} + a_{21}t & k_1 < t \le k_2 \\ \cdots & \cdots \\ a_{m0} + a_{m1}t & k_{m-1} < t \le n \end{cases}$$

where n is the length of the time series, k_1, k_2, … , k_{m-1} are structural change points in the intervals (k_1 - k_2,…, k_{m-2}-k_{m-1}), m-1 is the number of structural change points, and a_{11}, a_{21}, ., a_{m1} are the linear rates in the respective interval periods.

2) Determination of abnormal fluctuated periods for time series

Generally, an anomaly time series of over 1–3 times the standard deviation is defined as a statistically significant fluctuation. In this study, statistically significant fluctuations, which occurred in the time series of industrial output value, industrial products, power generation, and NO_2 densities in the YRD, presented an anomaly that was over 1.5 times the standard deviation. This method was used to identify the period of the financial crisis for all time series with structural changes.

III. Results

A. Spatial Dstributions of NOx Emissions and Tropospheric NO_2 Densities

Table I shows that the thermal power industry had the largest NO_x emission in the YRD, accounting for 47.82% of total emissions in 2008; the road-transport sector had the second-largest NO_x emission, accounting for 21.37% of total emissions. The largest NO_x emission from the thermal power industry was more than twice that from the road-transport sector, showing that the thermal power industry was the main source of NO_x emissions in the YRD. The central part of the YRD, consisting of Shanghai, Suzhou, Wuxi, Ningbo, and Nanjing, had the highest NO_x emissions. In this part, annual NO_x emissions were over 10 million tons for four of these cities, and the total NO_x emissions amounted to 132.93 million tons, accounting for 72.13% of the whole regional NO_x emissions in 2008, as seen in Table I. NO_x emissions from the thermal power industry in the central part of the YRD accounted for 35.06% of total regional emissions. Large thermal power plants with an installed capacity of more than 50 MW, which are mainly concentrated in this part of the YRD, accounted for 25% of the total amount of thermal power plants in the YRD [29], which emit most of the local NO_x emissions. It can be seen that only about 109,000 tons of NO_x were removed in the YRD, which amounts to 5.91% of total emissions. Since the power industry produces elevated levels of NO_x, these emissions extend over a larger area than those of such lower NO_x emissions sources as dense traffic and urban living. When there are fluctuations in thermal generating capacity within the region, the NO_x pollution could fluctuate correspondingly.

TABLE I: TOTAL AMOUNT OF NO_X EMISSIONS IN MAJOR CITIES OVER THE YRD IN 2008 [A] (UNIT: 0.1 MILLION TON)

City	Removal	Industrial sources	Urban living sources	Traffic sources	Thermal plants	Traffic percentage	Thermal plants percentage
Shanghai	2.01	31.6	15.98	15.63	23.41	32.85	49.2
Suzhou	4.58	29.42	4.39	3.6	17.06	10.65	50.46
Wuxi	0	16.54	4.58	3.76	9.59	17.8	45.41
Ningbo	0.88	15.13	1.96	1.84	9.23	10.77	54.01
Nanjing	1.9	9.19	4.14	3.39	5.33	25.43	39.98
Hangzhou	0.82	8.15	1.69	1.59	4.97	16.16	50.51
Jiaxing	0.25	7.14	2.82	2.65	4.36	26.61	43.78
Yangzhou	0.19	5.96	0.73	0.6	3.46	8.97	51.72
Huzhou	0	5.6	3.79	3.56	3.42	37.91	36.42
Changzhou	0.05	4.31	0.21	0.17	2.5	3.76	55.31
Nantong	0.21	4.06	1.15	0.94	2.35	18.04	45.11
Shaoxing	0.01	4.01	1.75	1.65	2.45	28.65	42.53
Sum	10.9	141.11	43.19	39.38	88.13	21.37	47.82

[a] Data are taken from China's annual statistic report on environment in 2008.

An analysis of OMI's NO_2 density variations shows that the monthly NO_2 density increased by 1.62×10^{15} molec.cm^{-2}

from October 2004 to September 2010 in the YRD. The largest increase of about 6.68×10^{15} molec.cm^{-2} occurred in winter. The high NO_2-polluted areas as observed by OMI generally correspond with the large NO_x emissions around the big cities and industrial zones in the YRD. The Shanghai metropolitan area, consisting of Wuxi, Suzhou, and Shanghai along the Yangtze River and situated in the central part of the YRD, has the highest averaged NO_2 tropospheric densities of about more than 2.0 × 10^{15} molec.cm^{-2}, as seen in Fig. 2a.

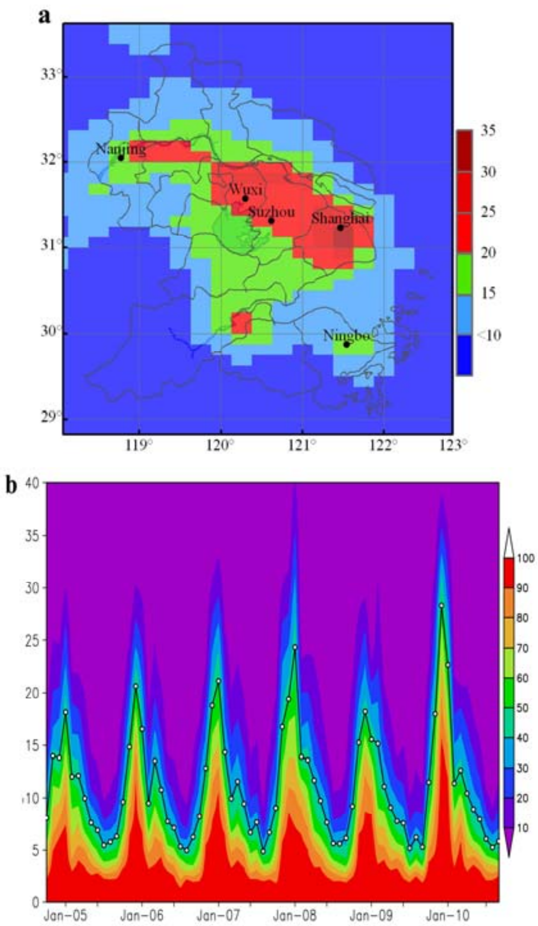

Fig. 2. Distribution of multi-year mean (a) and variations of monthly densities over different area covered proportions and the regional monthly densities (black line) (b) for NO_2 densities in YRD from OMI.

Regional monthly mean tropospheric NO_2 densities (the black line in Fig. 2b) underwent three variation periods. The first period, from October 2004 to October 2008, showed a rapid increase in tropospheric NO_2 densities; the largest increment of about 5.09×10^{15} molec.cm^{-2} occurred in winter from 2004 to 2008. The second period of November 2008 to February 2009 showed a significant decrease in tropospheric NO_2 densities: from winter 2007 to winter 2008, there was a decrease of 3.71×10^{15} molec.cm^{-2}. However, NO_2 densities rapidly increased again in the third period of March 2009 to September 2010; the NO_2 density increased to 21.16×10^{15} molec.cm^{-2} in winter 2009, which is over 5.30×10^{15} molec.cm^{-2} greater than in winter 2008. Furthermore, with the highest tropospheric NO_2 densities, which are less than 30% in Fig. 2b, the same three periods were also evident, the most significant fluctuations having also occurred in winter 2008, which was at the height of the financial crisis.

B. Comparison of Trends in NO2 Densities from Ground-Based Observations and OMI

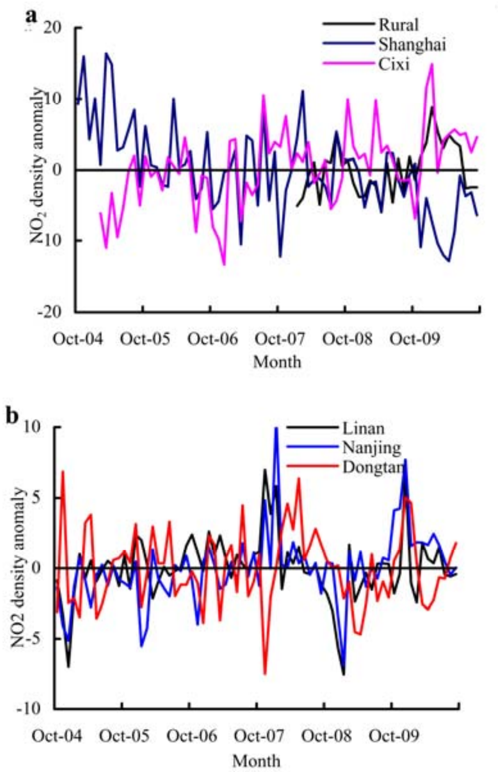

Fig. 3. Temporal variations of standardized NO_2 densities with from both ground-based observations (a) and OMI (b) in YRD (a μg•m^{-3}, b 1×10^{15} molec.cm^{-2}).

Fig. 3a and b shows comparisons of NO_2 densities from ground-based and OMI observations in cities (Shanghai, Cixi, Nanjing), industrial zones (Dongtan), and rural areas (Linan). Shanghai, the largest central industrial city in the YRD, showed a reduced trend in ground monthly averaged NO_2 density from October 2004 to September 2010, decreasing by 14.13μg•m^{-3}. But no significant fluctuations are evident in the ground-based NO_2 density in Shanghai during the financial crisis, as seen in Fig. 3a. In Cixi, a smaller city that underwent rapid industrialization in the YRD, the ground monthly mean NO_2 densities increased by 11.41μg•m^{-3} from January 2005 to May 2010. In line with the variations in ground NO_2 densities in Shanghai, no significant fluctuations occurred during the period of the financial crisis. The trend of ground monthly mean NO_2 densities in the rural station was the same as in Cixi, but the rate of increase was lower. It can be concluded that there was no significant fluctuation in ground-based NO_2 densities in the YRD, where lower emission sources dominate, e.g., dense traffic and urban living, during the period of the financial crisis. In contrast, significant fluctuations occurred in tropospheric NO_2 densities from OMI's observations over Linan, Nanjing, Shanghai, and Dongtan, which have different levels of industrial development, during the height of the financial crisis in winter 2008, as seen in Fig. 3b. In rural Linan, the tropospheric NO_2 density in winter 2008 was 43.88% and 33.7% lower than in winter 2007 and winter 2009, respectively. It can be concluded that fluctuations in NO_2 densities during the financial crisis mainly occurred in the troposphere over the cities, industrial zone, and rural area, not at ground level.

C. Impact of Industrial Downturn due to Fnancial Crisis on Tropospheric NO_2 Densities

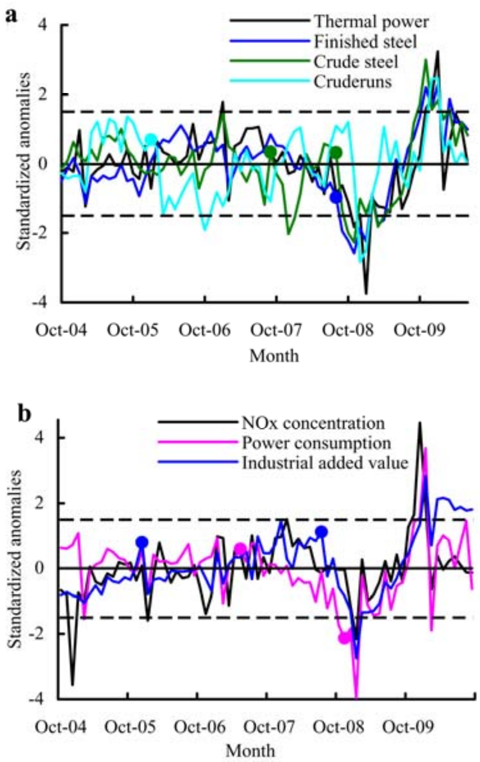

Fig. 4. Variations of the industrial outputs in three major industrial sectors (a) and regional averaged NO_2 density, power consumption and industrial added value (b) in YRD. The location of big spots appearing in the time series represents where the structural changes occurred.

The detection of local NO_x pollution fluctuations due to the financial crisis is linked to several factors, such as determination of the fluctuating period, magnitude of the NO_2 densities, consistency with the period of financial crisis, and local NO_2 density fluctuation. Three major industrial sectors, consisting of thermal power, smelting and pressing of ferrous metals, and petroleum processing, have the largest NO_x emissions among all industrial sectors in the YRD [22], [29], and they are used to represent the fluctuation in industrial production. The analyzed results show that monthly industrial products of these three industrial sectors experienced significant fluctuations from June 2007 to December 2009 according to the Chow test, as seen in Fig. 4a. Thermal power growth showed two structural breakpoints in July 2007 and November 2008. With crude steel, two structural breakpoints occurred in September 2007 and August 2008; a structural breakpoint occurred in January 2006 for crude iron. Correspondingly, the structural breakpoints appeared from May to November 2008 for tropospheric NO_2 densities, industrial power consumption, and industrial added value, as seen in Fig. 4b.

Parts of the structural breakpoints of each time series among mainly industrial products, industrial added value, thermal power, power consumption, and tropospheric NO_2 densities showed a distinct V-shaped fluctuation from May 2007 to December 2009, indicating that the financial crisis had a tremendous impact in terms of industrial production, power generation, energy consumption, and tropospheric NO_x pollution. Deviations in all time series were more than 1.5 times the standard deviation from November 2008 to February 2009, suggesting that the fluctuation is statistically significant. On the basis of fluctuations for all time series, November 2008 to February 2009 is defined as the worst period in the financial crisis. Major industrial products in this period decrease by 3.27%–12.10% over the same period of the previous year. When thermal power showed its maximum decrease of 12.10%, it led to tropospheric NO_2 density decreasing by 16.97% over the same period of the previous year. When thermal power capacity increased by 29.63% in the same period of the following year, when the effect of the financial crisis was weaker, tropospheric NO_2 density correspondingly increased by 30.07%. Therefore, the financial crisis from November 2008 to February 2009, which caused the industrial slowdown and a decrease in thermal power, significantly affected regional NO_2 pollution in the YRD.

IV. Conclusions

The financial crisis exerted a tremendous impact on all industrial production, power generation, and energy consumption. During the financial crisis, fluctuations in NO_2 pollution are also evident using the NO_2 column products derived from OMI. Furthermore, parts of the structural breakpoints of each time series among major industrial products, industrial added value, thermal power, power consumption, and tropospheric NO_2 densities presented a distinct V-shaped fluctuation from May 2007 to December 2009. All time series show the greatest fluctuation of more than 1.5 times the standard deviation at the height of the financial crisis, from November 2008 to February 2009. At the height of the financial crisis, the YRD experienced significant fluctuations in tropospheric NO_2 densities in response to the industrial downturn. Thermal power fluctuations were mainly responsible for the NO_2 fluctuations. From November 2008 to February 2009, thermal power showed a maximum decrease of 12.10%, leading to tropospheric NO_2 density decreasing by 16.97% over the same period of the previous year. When thermal power capacity increased by 29.63% in the same period the following year, when the effect of the financial crisis had declined, tropospheric NO_2 density correspondingly increased by 30.07%. The thermal power industrial sector accounts for the greatest coal consumption and highest NO_x emissions in the YRD. The smelting and pressing of ferrous metals sector and the sector manufacturing communications and computer equipment have the greatest industrial output and electricity consumption. Since electricity is mainly obtained from local coal-burning thermal plants without NO_x-processing equipments and the coal-based energy structure will not change in the short term, installing NO_x-removal devices in thermal power plants is an important and feasible way of controlling regional NO_x emissions and pollution in the YRD. In the long run, it will be necessary to improve electricity production and the industrial structure and develop clean alternative energy sources to provide a fundamental solution to local NO_x pollution.

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