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Original Research Paper

Spatio-Temporal Variations of Urban NO_2 Concentrations in China

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ABSTRACT

The spatial and temporal characteristics of NO_2 concentration were analysed from 31 cities in China over a six-year period (2003-2008). Urban NO_2 concentrations were in the range of 12-73µg/m^3, and its pollution levels had an expanding trend in the temporal variations during 2003-2008. Spatially, there was an evident difference for urban NO_2 concentration in the three regions of the eastern, central and western China. NO_2 concentrations in cities had a significant reduction in eastern China, an obviously heightened trend in central China and a small heightened trend in western China due to the combined effects of industrial structural transformation and industrial upgrading, as well as control measures.

INTRODUCTION

Atmospheric nitrogen pollution is a very topical environmental issue, and captures the attention of policy makers (Curtis et al. 2006, Zhang et al. 2007, Shon & Kim 2011). NOx (NO + NO_2) has been one of the most important pollutants in urban areas for its massive discharge from motor vehicle exhaust and stationary sources such as electric utilities as well as the rapid development and industrialization (Zhang et al. 2007, Zhu et al. 2012, Ozkurt et al. 2013). Environmental NO_2 is also a potential risk factor for summer smog, acid rain and ischemic stroke and vascular dementia (Latza et al. 2009, Andersen et al. 2009, Li & Xin 2013).

Driven by rapid socioeconomic development and intensive energy use, NO_2 emissions and their impacts have evolved into a serious environmental challenge for China (Wang et al. 2009, Takashima et al. 2011). In China, energy consumptions and motor vehicles especially for private cars are increasing rapidly in recent years, which led to the swift growth of urban NO_2 emission. Moreover, NOx index was eliminated while NO_2 index was slacked in the "Ambient Air Quality Standards (GB3095-1996)", which also led to an increase of NO_2 concentration in cities (Chen & Yu 2010). NO_2 emission from thermal power plants added 2.4 million tons during the only six years (1999-2004), which was the sum of that in the 12 years (1987-1998). Beijing and regions of northeastern China were found to be the seriously polluted area of the world (Richter et al. 2005). In the future 30 years, NO_2 emission would continue to grow steadily and become the largest country beyond USA under the present controlling measures which inflict suffering on the public health and the ecological environment development (Zhou et al. 2008, Fang et al. 2010, Loft et al. 2012, Li & Xin 2013).~

Under environmental pressure, China's government is attempting to shift its development mode from one dependent on intense fossil energy inputs with consequent high emissions to a more resource-efficient and environment-friendly alternative (Wu 2009). However, current policies and regulations of NO_2 control are still not perfect in such a short history in China. Taking the NO_2 emission standard for example, the limit values are given only in power plants and motor vehicles (Zhang et al. 2008). Moreover, prior studies mostly concerned in local regions and a certain province (autonomous region, and municipality directly under the central government) for discussing the spatio-temporal variations and sources of NO_2/NOx (Zhang et al. 2007, Chen et al. 2010, Li & Wang 2011) and urban photochemical air pollution (Zhang et al. 1998, Li 2009). As for the national scale, more researchers used the satellite measure to map the spatial variations of tropospheric NO_2 columns (Richter et al. 2005, Zhang et al. 2007, Wang et al. 2009) while less applied the geo-statistical method to understand the spatial and temporal variations of NO_2 concentration. In this study, the long-term trends of urban NO_2 concentrations were evaluated, and its spatial distributions on a national scale were done by a geo-statistical method for NO_2/NOx control strategy establishment, further for the harmonious development of the national environment and economy.

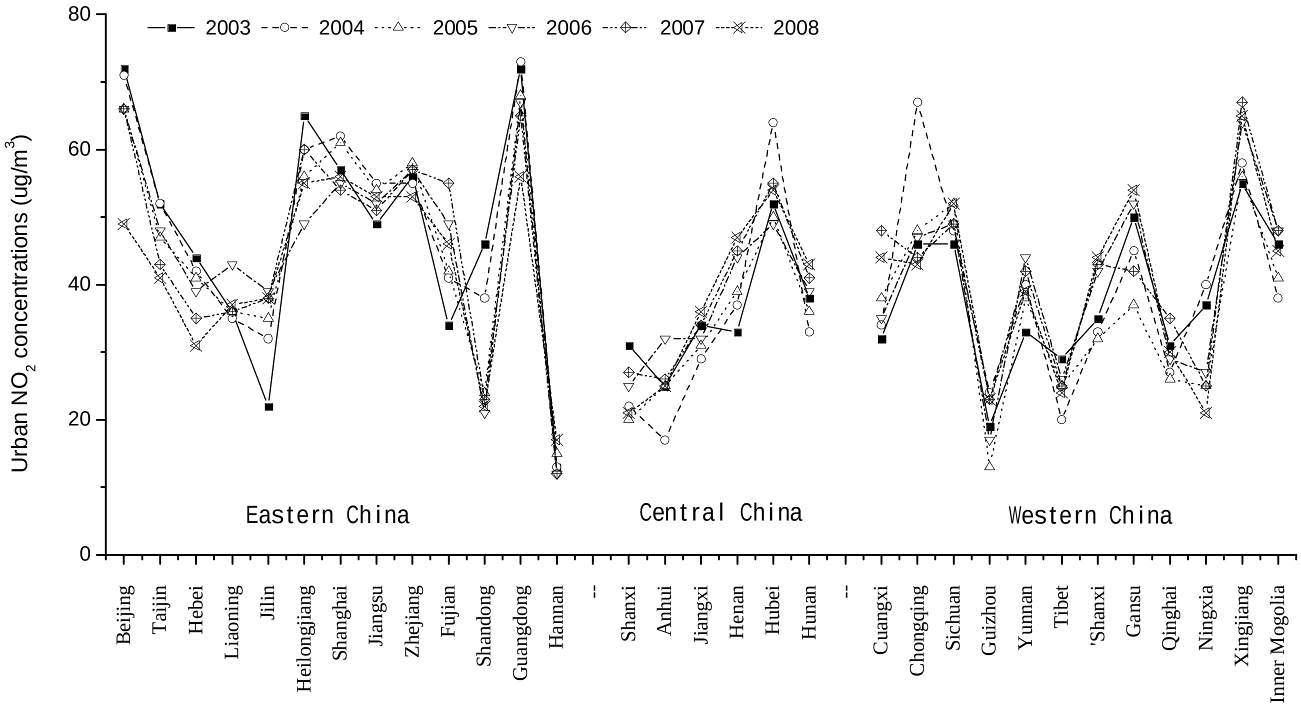

Fig. 1: Urban NO_2 concentration of 31 provinces (autonomous regions and municipalities directly under the Central Government, excluding Taiwan province, Hong Kong and Macao Special Administrative Region) during 2003-2008. Geographically, China is divided into the eastern (including Beijing, Tianjin, Hebei, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan provinces), the central (including Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan provinces) and the western region (including Guangxi, Chongqing, Sichuan, Kunming, Tibet, 'Shanxi, Gansu, Ningxia, Xinjiang, Inner Mongolia autonomous region).

METHODS AND SOURCES OF DATA

Data sources: All the data of NO_2 concentrations (μg/m^3) and the number of population used in this study were from "The China Year Books" during 2004-2009. There is usually no data integrality for the index of NO_2 concentration is not monitored in urban monitoring standard, so urban NO_2 concentrations in the capital 31 cities (exclude Taiwan) replaced those in their corresponding provinces, as shown in Fig. 1.

Measurement of regional difference: Standard error (SE) is a common method to measure regional absolute difference. Due to the effect of the increasing population, a single *SE* does not to test completely regional differences of NO_2 concentrations. What is more, the two indexes above cannot be decomposed into formal between-group and within-group difference. Thus, all of the *SE*, coefficient of variation (CV) and Theil (1967) measures were used to analyse the difference in the study, and the relative formulates above are as follows:

$$SE = \sqrt{\sum_{j=1}^{n} (Y_j - \overline{Y})^2 / n} \qquad ...(1)$$

Where *SE* is the standard error, Y_j is urban NO_2 concentration of province j, $\overline{Y}$ is the annual average, and *n* is the number of provinces.

$$CV = \sqrt{\sum_{j=1}^{n} \left(Y_j - \overline{Y}\right)^2 / p_j / \overline{Y}} \qquad ...(2)$$

Where *CV* is the weighted coefficient of variation, p_j is the proportion of province *j* in the whole nation population. Both Y_j and $\overline{Y}$ are the same as the formula (1) above.

$$T = BT + WT = \sum_{i=1}^{m} G_i \log(G_i / p_i) + \sum_{i=1}^{m} G_i \sum_{j=1}^{t} (g_i / G_i) \qquad ...(3)$$

Where *T* is the Theil, *BT* is the between-group Theil, *WT* is the within-group Theil, *m* is the number of the decomposed region, *t* is the number of provinces of *i* region, *Gi* is the proportion of region *i* of the whole nation NO_2 concentration, p_i is the proportion of province *j* in the whole nation population, g_i is the proportion of province *j* in region *i* of the whole nation NO_2 concentration, p_i is the proportion of province *j* in region *i* of the whole nation population.

Exploratory spatial data analysis (ESDA): Exploratory

Table 1: Proportions and decompositions of differences in urban NO_2 concentrations using Theil index (2003-2008).

Year	T	WT	BT
2003	0.4105	0.3935 (95.9%)	0.0170 (4.1%)
2004	0.4179	0.3976 (95.2%)	0.0203 (4.8%)
2005	0.3646	0.3488 (95.7%)	0.0158 (4.3%)
2006	0.3411	0.3257 (95.5%)	0.0155 (4.5%)
2007	0.3265	0.3115 (95.4%)	0.0151 (4.6%)
2008	0.3186	0.3026 (95.0%)	0.0160 (5.0%)

Table 2: The number of categories I, II and III in different provinces.

	I	II	III
2003	15	13	3
2008	9	13	8

spatial data analysis (ESDA) extends exploratory data analysis to spatial data for the process of spatially distributed visualization, the identification of atypical location or outliers, the representation of spatial association pattern, the identification of spatial cluster or hotspot, coldspot, and spatial regime as spatial heterogeneity. In this study, Getis-Ord Gi* was used to evaluate hotspots and coldspots spatial pattern from the observed data. The value of G* would be positive if the clustering happened in one observed data result or that value is more than mean and the value of G* would be negative if the clustering value which is less than mean happened in one observed data result (Joko-Prasetyo et al. 2012). The equation of G* statistic could be defined as in the equation (4).

$$G^* = \sum_{j=1}^{n} W_{ij}(d) Z_j \, / \sum_{j=1}^{n} Z_j \quad ...(4)$$

Based on this equation, is the element of spatial weight matrix and (*d*) is the element of distance inter spatial object.

RESULTS AND DISCUSSION

Temporal variations of urban NO_2 concentration: During 2003-2008, urban NO_2 concentrations were in the range of 12-73μg/m^3 (Fig. 1), and the NO_2 level of 46.2% (±5.4%) cities attained Grade I (0-40μg/m^3) with a downward trend while others were in Grade II (40-80μg/m^3) with an upward trend on the whole. Fig. 2 exhibits that the annual average concentrations of urban NO_2 vary from 39.8 to 42.4 μg/m^3, and have a descending-ascending phase while both their *CV* and *SE* have a similarly descending trend. During 2003-2005, the annual average concentrations had the descending phase with a degree of 4.3%, and their *CV* and *SE* had the stock declining trend. And then, the annual average concentrations had the ascending phase with a degree of 2.3%, while their *CV* and *SE* had the declining trend year by year during 2005-2008. The results above indicated that urban NO_2 pollution had an expanding trend in the temporal variations during 2003-2008.

Spatial variations of urban NO_2 concentration: Based on the urban NO_2 concentrations and the numbers of population, the Theil indexes including *WT* and *BT* were calculated during 2003-2008 (Table 1). The *T* and *BT* reduced by 11.19% and 11.37% during 2003-2005 while by 12.61% and 13.24% during 2005-2008, respectively. The proportion of *BT* to *T* increased from 4.1% to 5.0% and that of *WT* to *T* reduced from 95.9% to 95.0%. As for the contributions of *WT* to *T* and *BT* to *T*, *BT* from eastern, central and western China contributed from 94.97% to 95.86% to *T* of the whole China. This also indicated that there was a visible descending trend for the regional differences of urban NO_2 concentrations due to their inner differences of urban eastern, central and western China.

Distributions of urban NO_2 concentration types: Based on the general trend of urban NO_2 concentration during 2003-2008 (Fig. 2), the NO_2 concentrations in the two years (2003 and 2008) were selected and its Getis-Ord Gi* values were calculated by the ESDA mode of ARCGIS software (ver. 9.3). And the natural breakpoint in descending order scores was used to classify the provinces as category I, II and III, as shown in Fig. 3. The number of category I, II and III in different provinces were also made statistically, as given in Table 2.

On the whole, there were a large number of provinces in category I degree and the smallest amount of provinces in category III degree (Table 2). The number of provinces in category I degree reduced from 15 in 2003 to 9 in 2008 with a high degree of 40%. The number of provinces in category II degree stayed the same (13), but the amount of provinces in category III degree increased from 3 in 2003 to 8 in 2008. The results showed that urban NO_2 pollution was rather serious with a severe "duality" in China, which due to the combined effects of industrial structural transformation and industrial upgrading (Yang 2008, Wang et al. 2009, Chen et al. 2012). Fu et al. (2011) found most polluting industries in central and western China were higher than that of the eastern regions during 2003-2008 and would bound to transfer to western regions in the future. Liu et al. (2012) also found power industry and agro-food processing industry had appeared to shift to the central and western regions since 2001 while paper products industry, non-metallic mineral products industry began to shift to the central region in 2006. Moreover, economic development model and industrial restructuring in China proved that the optimization of industrial structure was the guarantee of harmonious development of economic construction and environmental governance

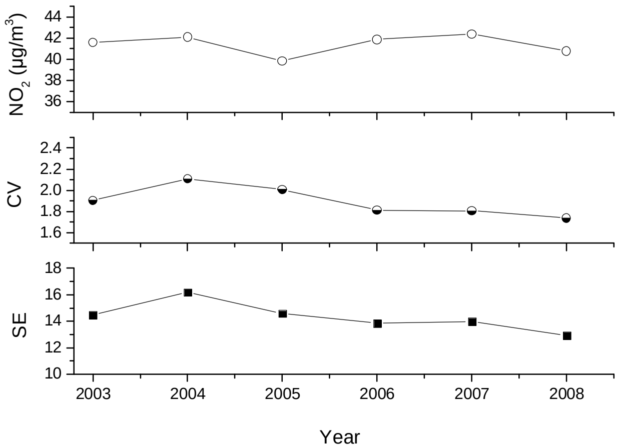

Fig. 2: Annual average values of urban NO_2 concentrations, their standard errors (*SE*) and coefficients of variation (*CV*) in China during 2003-2008.

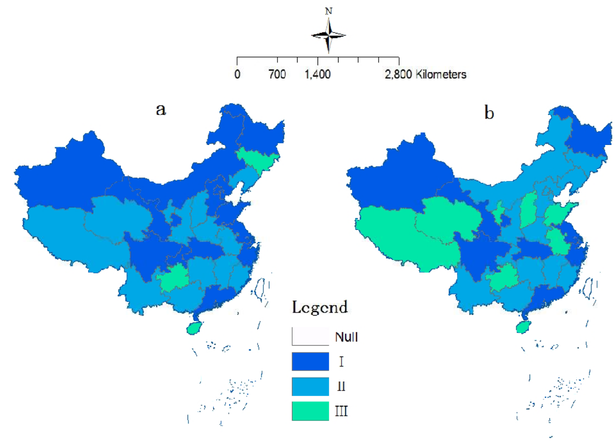

Fig.3: Degree distributions of urban NO_2 concentration in 2003 (a) and 2008 (b).

(Zhang 2012). A research on industrial pollution in different industrial sectors showed that changes in industry structure among industrial sectors have a significant influence on pollution in China's high pollution intensity industries sectors and low and middle pollution intensity industries (Jiang 2010). The industrial pollution transferred from the eastern areas to central and western areas as well as industrial transfer in eastern areas, which may cause more serious NO_2 pollution and inevitably further deteriorate ecological environment in central and western areas while alleviate the NO_2 pollution of eastern China.

Regionally, the category I of urban NO_2 concentration appeared mainly in eastern China while other categories (II and III) concentrated mainly in western China (Fig. 3), which was in good agreement with the characteristics of NOx emission and reduction potential and the transfer of pollution-intensive industries in China (Yang 2008, Wang et al. 2010). Nowadays, with the entrance into WTO and the development of western regions, increasing overseas investments have been introduced to western regions, including some pollution-intensive industries refused by the eastern area. The moving eastward of industrial output and the westward of industrial contamination bring some pollution, and burdened the weakened biological environment in the west regions.

Compared with Fig. 3a and Fig. 3b, the degree of urban NO_2 concentration in Shanghai, Jiangsu and Zhejiang province of the Yangtze River Delta Economic Zone and Guangzhou province kept stable in the category I in 2003 and 2008, which indicated that urban NO_2 pollution was significant, though their regional economic development was in the rapid growth stage. The degree of NO_2 concentration in Hubei, Gansu and Sichuan province was also steady in the category I in 2003 and 2008, which suggested that the three provinces are in the relatively developed industry region of central-west China, environment protection must be enhanced and the ability of continuous development also is improved in undertaking industrial transformation. Moreover, the category II regions kept stable in Liaoning and Fujian province of eastern China, Henan, Hunan and Jiangxi province of central China, and Yunnan, Guangxi and 'Shanxi province of western China, while the category III regions in Hainan province of eastern China and Guizhou province of western China.

Degree distributions of urban NO_2 concentration changed in some provinces between 2003 and 2008 (Fig. 3a, 3b). The degree of urban NO_2 concentration in the regions of Beijing, Tianjin and Hebei province (Jing-Jin-Ji region) changed from the category I in 2003 to II in 2008, which was attributed to the government policy for the Beijing 2008 Olympic Games. In order to heed the call for the Green Beijing Olympic Games, long-term effective measures of controlling atmospheric pollution such as controlling automobiles emission were taken by increasing investments in Beijing and its neighbouring regions of Tianjin and Hebei province, which led to the decline of regional NO_2 concentration (Yu et al. 2009, Li & Wang 2011). In addition, the degrees of urban NO_2 concentration had highly reduced in those provinces: the category in Shandong and Inner Mongolia from I in 2003 to III in 2008, in Chongqing from I to II, and in the regions of Anhui, Tibet, Ningxia and Qinghai from II to III (Figs. 3a, 3b).

Spatial distributions of urban NO_2 concentrations: In order to discuss the dynamic changes of urban NO_2 concentrations in a spatial scale, the two regions of the increased and decreased regions (Fig. 4) were done by the Manual Classify method in the ARCGIS software during the two stages

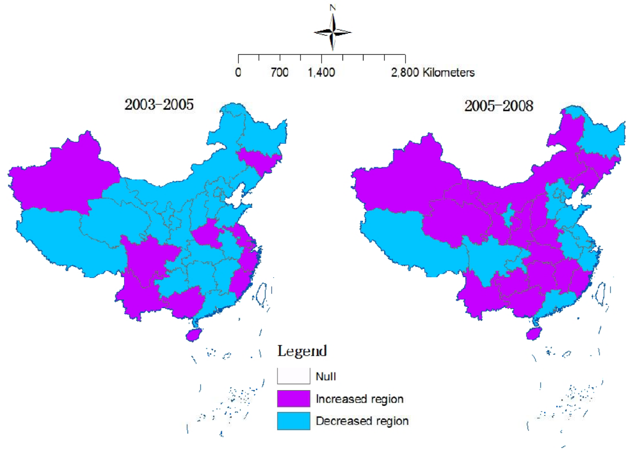

Fig.4: The increased and decreased regions during the two stages (2003-2005, 2005-2008).

sify method in the ARCGIS software during the two stages (2003-2005, 2005-2008) based on Fig. 1.

The number of increased provinces had an increasing trend during 2003-2008, as shown in Fig. 4. There were 12 and 17 provinces belonging to the increased regions during 2003-2005 and 2005-2008, respectively. As for regional distributions, the numbers of increased provinces in eastern, central and western China were six, one and five during 2003-2005 and four, five, eight during 2005-2008. That is to say, there had a significant reduction in eastern China, an obviously heightened trend in central China and a small heightened trend in western China. This result above, again, proved that the tendency towards worsening NO_2 pollution has been arrested in eastern China where the ability of sustainable development has been improved. But the regions of NO_2 concentration increase has been spreading and the regional ability of sustainable development needed further improvement in central and western China, which should be paid attention to industry, academe and government.~

Compared to Fig. 3 and Fig. 4, the NO_2 concentrations in Jiangsu, Hubei, Xinjiang, Gansu and Sichuan province were in both the category I and the increased regions, which indicated that regional NO_2 pollution was relatively serious. Though the NO_2 concentrations were in the category III in Hainan and Guizhou province and in the category II in those provinces of Liaoning, Fujian, Henan, Hubei, Jiangxi, Yunnan, Guangxi and Shanxi, all of these provinces were in the increased regions, which suggested that regional NO_2 pollution had a worsening tendency. There was an effective pollution treatment for NO_2 emission for regional NO_2 concentrations were declining in Heilongjiang, Zhejiang, Shanghai and Guangzhou provinces though the provinces were in the category I. What is more, regional NO_2 concentrations declined from the category II to category III in Shanxi, Tibet, Ningxia, Anhui, Qinghai province and from the category I to II in Beijing, Tianjin, Hebei, Shandong, Inner Mongolia and Chongqing. At the same time, all of the 11 provinces above were in the declined region. This indicated that NO_2 emission had a good control in the 11 provinces of China.

CONCLUSIONS

NO_2 concentrations from 31 cities in China over a six-year period (2003-2008) were used for the study of temporal and spatial distribution. Urban NO_2 concentrations were in the range of 12-73µg/m^3, and its pollution levels had an expanding trend in the temporal variations during 2003-2008. Spatially, there was a ~visible descending trend for the regional differences of urban NO_2 concentrations due to their inner differences of urban eastern, central and western China. NO_2 concentrations in cities had a significant reduction in eastern China, an obviously heightened trend in central China and a small~heightened trend in western China due to the combined effects of industrial structural transformation and industrial upgrading.

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