Impact of urbanization level on urban air quality: A case of fine particles (PM_{2.5}) in Chinese cities

Lijian Han ^a, Weiqi Zhou ^{a,*}, Weifeng Li ^a, Li Li ^b

^a State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

^b School of Urban Planning and Design, Peking University Shenzhen Graduate School, Shenzhen 518055, China

ARTICLE INFO

Article history:

Received 9 April 2014

Received in revised form

25 June 2014

Accepted 17 July 2014

Available online 9 August 2014

Keywords:

Urbanization

Air pollution

Fine particulate matter (PM_{2.5})

Chinese prefectures

ABSTRACT

We examined and compared PM_{2.5} concentrations in urban and the surrounding regions, and further investigated the impact of urbanization on urban PM_{2.5} concentrations at the Chinese prefectures. Annual PM_{2.5} concentrations in most prefectures were greater than 10 µg/m³, the air quality guideline of the World Health Organization. Those prefectures were mainly distributed along the east coast and southeast of Sichuan province; The urban PM_{2.5} concentrations (Urban_{PM_{2.5}}) in 85 cities were greater than (>10 µg/m³) those in the surrounding area. Those cities were mainly located in the Beijing–Sichuan and Shanghai–Guangxi belts. In addition, Urban_{PM_{2.5}} was less than (<10 µg/m³) that in surrounding areas in only 41 prefectures, which were located in western China or nearby mega cities; Significant positive correlations were found between Urban_{PM_{2.5}} and urban population ($R^2 = 0.99$, $P < 0.05$), and between Urban_{PM_{2.5}} and urban second industry fraction ($R^2 = 0.71$, $P < 0.05$), suggesting that urbanization had considerable impact on PM_{2.5} concentrations.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Since the early 1980s, China's rapid economic growth has been accompanied by a rapid urbanization. The urban population proportion in China has increased from 18% in 1978 to 52% in 2012, and it is projected that 65%, or approximately one billion people will live in cities by 2030 (Zhu et al., 2011). This growth in such a short period has not only led to an improvement in material wealth and a higher standard of living, but also caused severe environmental pollution, particularly air pollution, in many urbanized regions of China (Chan and Yao, 2008; Huang et al., 2009).

As a major urban air pollutant, the concentrations of fine particulate matter (PM_{2.5}) directly affected by both human activity and the surrounding environment (Chan and Yao, 2008). However, urban and rural areas do not exhibit homogenous of PM_{2.5} concentrations. Because PM_{2.5} is mainly caused by human activities, the average concentration patterns observed between urban and rural areas can be varied and conflicting: 1) As a center of human activity, urban area generate a great amount of air pollutant emissions, which can result in larger PM_{2.5} concentrations in urban area than in surrounding areas (von Bismarck-Osten et al., 2013; van

Dingenen et al., 2004); 2) In harsh environment areas, e.g. dust emission areas where PM_{2.5} concentration is higher than other natural ecosystems (Han et al., 2013), green and ecological urban construction can mitigate environmental particulates and PM_{2.5} concentrations inside a city (Yang et al., 2008), which can result in lower PM_{2.5} concentrations in urban areas than in surrounding areas; 3) In some urban areas with better environmental protection or more severe pollution, urban and surrounding areas can have similar PM_{2.5} concentrations, indicating that urban pollution has not reached PM_{2.5} capacity or the surrounding areas have reached PM_{2.5} capacity due to urban PM_{2.5} pervasion (Burton et al., 1996). Different urban PM_{2.5} concentration levels are highly attributable to the imbalance in China's urbanization development (Fang and Liu, 2009), in addition to natural effects such as Asian dust storms (Han et al., 2013). Three indicators, urban built-up area, population and industry fraction, can illustrate the level of urban human activity, suggesting an interface to indirectly describe urban PM_{2.5} concentration variation (Zhao et al., 2012).

High concentrations of particulate matter (PM), particularly PM_{2.5}, have raised great concern due to its effects on visibility impairment (Hyslop, 2009) and public health (Pope and Dockery, 2012), as well as its increasing annual portion of major urban air pollutants in Chinese cities (Wang and Hao, 2012). Data from model simulation and satellite imagery suggests that PM_{2.5} concentrations are higher in many regions of China than in other countries,

* Corresponding author.

E-mail addresses: world.han@gmail.com (L. Han), wzhou@rcees.ac.cn (W. Zhou).

particularly urban areas (e.g. van Donkelaar et al., 2010). However, few studies have quantitatively examined the spatial pattern of $PM_{2.5}$ concentrations in Chinese cities, and the impact of urbanization on $PM_{2.5}$ concentrations (Lin et al., 2014). This information is critically important for China to achieve the goals of the recently released long-term plan for controlling air pollution (http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm). The objectives of this study were 1) to examine the $PM_{2.5}$ concentration differences between urban and surrounding areas, to determine the impact of urban $PM_{2.5}$ emissions on surrounding areas, and 2) to investigate the relationship between urbanization, expressed by built-up area, population and secondary industry fraction, and $PM_{2.5}$ pollution in Chinese cities.

2. Study area and materials

2.1. Study area

The basic administrative unit between province and county is the prefecture, which can be used to demonstrate China's urban environmental pollution and protection activities, as well as China's rapid urbanization. In addition, the social economic records well match the $PM_{2.5}$ concentration distribution at prefectural level. Prefectures were, therefore, used as the basic study unit to understand urban $PM_{2.5}$ concentrations and their relationship with urbanization in China (Fig. 1).

2.2. Fine particulate matter ($PM_{2.5}$) data

PM, especially $PM_{2.5}$, has negative effects on human health, including both morbidity and mortality (Pope and Dockery, 2012). Many developed countries have established monitoring networks

for $PM_{2.5}$ detection (Engle-Cox et al., 2004). Despite suffering the most severe $PM_{2.5}$ pollution (Mage et al., 1996), few developing countries (e.g. China) have created monitoring networks (Zheng et al., 2009). Those networks have limited spatial distribution, however, making it difficult to quantitatively illustrate the spatial pattern of $PM_{2.5}$ concentrations. Thus, the application of remote sensing in $PM_{2.5}$ concentration estimation was developed. Many researches have considered the relationship between aerosol optical depth (AOD) and $PM_{2.5}$ concentration, and explored it via simple empirical approaches or complex physical/meteorological models (e.g. van Donkelaar et al., 2010).

The $PM_{2.5}$ concentration used in this research was estimated from remotely sensed aerosol optical depth (AOD) multiply a conversion factor which is a function of the factors that relates to 24 h dry aerosol mass to the AOD (van Donkelaar et al., 2010). In practice, based on a simulation of the GEOS-Chem chemical transport model, the $PM_{2.5}$ concentrations were estimated from the combination of Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) AOD with aerosol vertical profiles and scattering properties (van Donkelaar et al., 2010). The global $PM_{2.5}$ concentration dataset had a spatial resolution of 10 km as annual average during 2001–2006 (van Donkelaar et al., 2010). In this study, we used a subset of the global $PM_{2.5}$ concentration dataset that covered China at a relative humidity of 35%, which is the surface measurement standard that the U.S. and Canada utilize for $PM_{2.5}$ concentration measurement.

2.3. Urban distribution, prefectural boundary, and social economic records

The MODIS global map of urban distribution with a spatial resolution of 500 m was utilized to separate urban from non-urban

Fig. 1. Chinese prefectures.

areas (Schneider et al., 2009, 2010). The prefectural boundary layer with a scale of 1:250,000 was obtained from the National Geomatics Center of China (<http://ngcc.sbsm.gov.cn/>). The size of the urban built-up area, urban population, and fraction of secondary industry (e.g. heavy industry, real estate) in Chinese major cities were collected from the China City Statistical Yearbook 2006, and were used as indicators of urbanization.

3. Methodology

3.1. $PM_{2.5}$ concentration differences

Mean $PM_{2.5}$ concentrations were firstly summarized at the prefecture level using the $PM_{2.5}$ concentration dataset and prefectural boundary layer. The $PM_{2.5}$ concentration in the urban/non-urban areas ($Urban_{PM_{2.5}}/NonUrban_{PM_{2.5}}$) were then calculated based on the MODIS global urban map in each Chinese prefecture. The differences in $PM_{2.5}$ concentration ($D_{PM_{2.5}}$) between $Urban_{PM_{2.5}}$ and $NonUrban_{PM_{2.5}}$ were obtained with the following equation:

$$D_{PM_{2.5}} = Urban_{PM_{2.5}} - NonUrban_{PM_{2.5}} \quad (1)$$

Furthermore, spatial grouping analysis was conducted for $D_{PM_{2.5}}$ to further understand the spatial regulation of $D_{PM_{2.5}}$.

3.2. Statistical analysis

To examine the effects of urbanization on $PM_{2.5}$ concentration, cities with built up area larger than 100 km², that is one pixel of the $PM_{2.5}$ concentration dataset, were selected to conduct correlation analysis between $Urban_{PM_{2.5}}$ and urbanization indicators. Cities were divided into six groups based on the size of the built-up area with equal interval classification method, 100–200 km², 200–300 km², 300–400 km², 400–500 km², 500–1000 km², and larger than 1000 km², to examine the correlation between city size in terms of built-up area and $Urban_{PM_{2.5}}$. To quantify the relationship between urban population and $Urban_{PM_{2.5}}$, cities were classified into five population groups: less than 0.5 million, 0.5–1 million, 1–3 million, 3–10 million, and larger than 10 million (Niu et al., 2013). In addition, we classified cities into five groups based on secondary industry fraction with equal interval classification method, less than 30%, 30–40%, 40–50%, 50–60%, and larger than 60%, to investigate the relationship between urban industry fraction and $Urban_{PM_{2.5}}$. One-way analysis of variance (ANOVA) was used to conduct comparisons among multiple urban groups, and Fisher's least significant difference (LSD) was adopted to examine the differences between groups. Pearson correlation analysis was carried out between $Urban_{PM_{2.5}}$ and urbanization indicators (urban built-up area, population and secondary industry fraction) to explore the impact of urbanization on $PM_{2.5}$ pollution.

4. Results

Only 24 out of 350 Chinese prefectures had an annual $PM_{2.5}$ concentration of less than 10 µg/m³ (Fig. 2B), which is the air quality guideline (AQG) of the World Health Organization (WHO). However, a total of 166 prefectures had annual $PM_{2.5}$ concentrations higher than the WHO Interim target-1 (35 µg/m³), which is associated with an increase of 15% in long-term mortality risk relative to the AQG level (WHO, 2005). Prefectures with higher $PM_{2.5}$ concentrations were distributed in the southeast of Sichuan province, in a belt from Tianjin and south of Hebei province, through the northeast of Henan province, east of Shandong province, northeast of Anhui province, and Jiangsu province and Shanghai (Fig. 2A).

Different spatial pattern of $D_{PM_{2.5}}$ was found (Fig. 3A). The $D_{PM_{2.5}}$ in most prefectures (223 out of 350) ranged from 0 to 10 µg/m³, and were negative in only 41 prefectures (Fig. 3B), primarily located in western of China except for Langfang, Jiading, and Zhuhai in the east and southeast of China, which were close to the mega cities of Beijing, Shanghai, and Guangzhou, respectively. 85 prefectures had $D_{PM_{2.5}}$ greater than 10 µg/m³ (Fig. 3B), which were mainly located at two belts (Fig. 4A): one from the north of Hebei province, through Beijing, Shanxi province, northwest of Henan province and south of Shaanxi province, and finally southeast of Sichuan province (the Beijing–Sichuan belt); and one from Shanghai, Zhejiang province, through the south of Anhui province, Hunan and Jiangxi provinces, and finally Guangxi and Guangdong provinces (the Shanghai–Guangxi belt). The $D_{PM_{2.5}}$ in the Beijing–Sichuan belt was larger than that in the Shanghai–Guangxi belt: Prefectures with levels 4, 5, and 6 are mainly located in the Beijing–Sichuan belt (Fig. 4).

We found a significant relationship between urban built-up area and $Urban_{PM_{2.5}}$ ($R^2 = 0.36$, $P < 0.05$; Fig. 5A), but no significant differences in $Urban_{PM_{2.5}}$ among the different built-up area groups ($F = 0.376$, $P = 0.864$); Furthermore, $Urban_{PM_{2.5}}$ was significantly correlated with population ($R^2 = 0.99$, $P < 0.05$; Fig. 5B), and significant differences were observed in $Urban_{PM_{2.5}}$ among population groups ($F = 2.96$, $P = 0.025$). For example, $Urban_{PM_{2.5}}$ in cities with 0.5–1 million people was significantly lower than that in cities with 1–3 million people ($P = 0.028$) and $Urban_{PM_{2.5}}$ in cities with less than 0.5 million people was significantly lower than that in cities with more than 10 million people ($P = 0.043$) (Fig. 4B); Our result also showed that $Urban_{PM_{2.5}}$ was significantly correlated with secondary industry fraction ($R^2 = 0.71$, $P < 0.05$; Fig. 5C), and there were significant differences in $Urban_{PM_{2.5}}$ among secondary industry fraction groups ($F = 3.122$, $P = 0.019$). For instance, $Urban_{PM_{2.5}}$ in cities with fraction of secondary industry less than 30% was significantly lower than that in cities with a secondary industry fraction range of 40–50% ($P = 0.009$) or large than 60% ($P = 0.006$) (Fig. 4B). No inverse “U” shape was found between urban $PM_{2.5}$ concentration and each variable.

5. Discussion

Economic development, energy consumption, industrial structures, and environmental background are diverse in Chinese cities (Fang and Liu, 2009; Chen et al., 2013). The economy has been developing earlier and faster in eastern China, particularly in the rapidly urbanized areas. This development consumes a great amount of energy, resulting in the large emission of air pollutants. Moreover, China's development in the past few decades has strongly favored GDP growth over environmental protection, creating pollution emissions in urban areas that have diffused to the surrounding areas. We found two belts with urban $PM_{2.5}$ concentrations higher than the surrounding areas. In the Beijing–Sichuan and Shanghai–Guangxi belts, those cities are major energy bases (e.g. cities in Shanxi province), mega cities with dense populations and intense human activity (e.g. Beijing), and heavy industry plots (e.g. cities in Hebei province), exhibited high levels of pollution and pollutants were often transported into the surrounding areas. Our results also revealed that only 24 prefectures exhibited air quality meeting the AQG of WHO, but approximately half (166 out of 350) of China's prefectures experienced high $PM_{2.5}$ pollution, although those prefectures were gathered at two major areas and covered less than one third of the country. This pattern was highly attributable to the different levels of development among Chinese prefectures, suggesting that different air pollution prevention and control measures should be considered across the country.

Fig. 2. Annual average $PM_{2.5}$ concentration at the Chinese prefecture level during 2001–2006. AQG represents World Health Organization (WHO) air quality guideline; IT-1, IT-2, and IT-3 are WHO Interim target-1, Interim target-2, and Interim target-3, respectively.

Fig. 3. Annual average PM_{2.5} concentration differences between urban and non-urban areas ($D_{PM_{2.5}}$) at the Chinese prefecture levels during 2001–2006.

Urbanization and economic development can, however, help improve urban environments due to environmental protection and urban green construction (Speak et al., 2012). Our findings showed that some cities located near dry desert in the west of China, which experience dust events that increasing both large particles and PM_{2.5}, had lower urban PM_{2.5} concentration. While, other cases of negative $D_{PM_{2.5}}$ were found in rapid urbanization areas, i.e.

Langfang in the Beijing–Tianjin urban agglomerations, Jiaxing in the Yangzi River delta urban agglomerations, and Zhuhai in the Pearl River delta urban agglomerations. The pollution inside those cities was highly attributable to the pollutant diffusion from nearby mega city, but eased inside the urban areas due to their environmental protection and relatively low pollutant emissions. These cases appear to be special in urban agglomerations of China.

Fig. 4. Spatial grouping analysis of annual average PM_{2.5} concentration differences between urban and non-urban areas ($D_{PM_{2.5}}$) at the Chinese prefecture levels during 2001–2006.

Further research exploring the dynamics of pollutant transportation within urban agglomerations is necessary to understand the interaction of air pollution inside urban clusters.

Urban form, including the physical layout, economic structure, and population, can reflect the magnitude of human activities. Previous research found that cities with relatively large population would induce heavy air pollution (Marshall, et al., 2007). Our results also indicated that population was significantly correlated with urban PM_{2.5} concentrations in China. Consistent with the

Environmental Kuznets Curve theory, air pollution and income per capita produce an inverse “U” shape (Yandle et al., 2002). In the present study, however, no inverse “U” shape was found between urban PM_{2.5} concentration and economic variables, indicating that this curve may be invalidated. Further analysis to validate the “U” curve under certain urban economic structures is required to establish a better urban economic development model that considers environmental sustainability and protection.

Fig. 5. Correlations of Urban_{PM_{2.5}} with urban built-up area size (A), urban population (B), and urban secondary industry fraction (C). Bars represent the range of at different urban built-up groups (A), urban population groups (B), and urban secondary industry fraction groups (C).

Currently, the global estimation of PM_{2.5} concentration adopted in this research provides a long-term average concentration suitable for relatively large-scale studies. However, we only utilized the annual average data from 2001 to 2006, due to the unavailability of national urban cover data and the urban cover data still needs further justification. Longer-term research is recommended once a better quality urban cover data is available. Moreover, higher spatial-temporal resolution PM_{2.5} concentrations with remote sensing to support detailed study at the urban scale are also required to better understand the impact of the urban landscape and human activity on urban air quality.

This study illustrated the differences in PM_{2.5} concentrations between urban and non-urban areas at the Chinese prefectures level, and quantified the correlation between Urban_{PM_{2.5}} and urbanization indicators. The present research has helped to clarify

urban environmental pollution under rapid urbanization in China. Future studies at certain urban and urban agglomeration scales are required to demonstrate the detailed mechanisms of the impact of urbanization on urban air quality.

6. Conclusions

Urban particulates, particularly PM_{2.5}, form a major portion of air pollutants that affect Chinese urban environment. We examined the differences in PM_{2.5} concentrations between urban and surrounding areas, as well as the effect of urban built-up area, population, and secondary industry fraction on PM_{2.5} concentrations, in Chinese prefectures and cities to better understand the impact of urbanization on PM_{2.5} concentrations. The following conclusions were found:

- (1) Annual PM_{2.5} concentration in most Chinese prefectures was greater than 10 $\mu\text{g}/\text{m}^3$ in a year (AQG of WHO). The most severe PM_{2.5} pollution zones were located in the southeast of the Sichuan province, and a belt in eastern China from Tianjin and south Hebei province to Jiangsu province and Shanghai.
- (2) $D_{\text{PM}_{2.5}}$ was greater than 10 $\mu\text{g}/\text{m}^3$ in 85 prefectures, which were mainly located in the Beijing–Sichuan and Shanghai–Guangxi belts. Negative values were obtained in 41 prefectures, which were primarily located in western China or nearby mega cities; and
- (3) A significant positive correlation was identified between urbanization indicators and Urban_{PM_{2.5}}, demonstrating the impact of urbanization on PM_{2.5} concentrations.

Acknowledgement

This research was a part of Project Spatiotemporal Pattern of Urbanized Regions' Particulate Matter (PM_x) and Its Relationship with Landscape Pattern supported by National Natural Science Foundation of China (NSFC41301199).

References

- Burton, R., Suh, H., Koutrakis, P., 1996. Spatial variation in particulate concentrations within metropolitan Philadelphia. *Environ. Sci. Technol.* 30, 400–407.
- Chan, C., Yao, X., 2008. Air pollution in mega cities in China. *Atmos. Environ.* 42, 1–42.
- Chen, M., Liu, W., Tao, X., 2013. Evolution and assessment on China's urbanization 1960–2010: under-urbanization or over-urbanization? *Habitat Int.* 38, 25–33.
- Engle-Cox, J., Holloman, C., Coutant, B., Hoff, R., 2004. Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality. *Atmos. Environ.* 38, 2495–2509.
- Fang, C., Liu, X., 2009. Temporal and spatial differences and imbalance of China's urbanization development during 1950–2006. *J. Geogr. Sci.* 19, 719–732.
- Han, L., Tsunekawa, A., Tsubo, M., Zhou, W., 2013. An enhanced dust index for Asian dust detection with MODIS images. *Int. J. Remote Sens.* 34, 6484–6495.
- Huang, W., Tan, J., Kan, H., Zhao, N., Song, W., Song, C., Chen, G., Jiang, L., Jiang, C., Chen, R., Chen, B., 2009. Visibility, air quality and daily mortality in Shanghai, China. *Sci. Total Environ.* 407, 3295–3300.
- Hyslop, N., 2009. Impaired visibility: the air pollution people see. *Atmos. Environ.* 43, 182–195.
- Lin, G., Fu, J., Jiang, D., Hu, W., Dong, D., Huang, Y., Zhao, M., 2014. Spatio-temporal variation of PM_{2.5} concentration and their relationship with geographic and socioeconomic factors in China. *Int. J. Environ. Res. Public Health* 11, 173–186.
- Mage, D., Ozolins, G., Peterson, P., Webster, A., Orthofer, R., Vandeweerd, V., Gwynne, M., 1996. Urban air pollution in megacities of the world. *Atmos. Environ.* 30, 681–686.
- Marshall, J., Sander, H., Manson, S., 2007. Air pollution and urban form: evidence from satellite data. In: 5th WSEAS International Conference on Environment, Ecosystem and Development, Tenerife, Spain, 14–16 Dec. 2007, pp. 463–465.
- Niu, F., Bai, J., Yang, Z., 2013. Annual Report on Development of Small and Medium-size Cities in China. Social Science Academic Press of China, Beijing, p. 2.
- Pope III, C., Dockery, D., 2012. Health effects of fine particle air pollution: lines that connect. *J. Air Waste Manag. Assoc.* 56, 709–742.
- Schneider, A., Friedl, M., Potere, D., 2009. A new map of global urban extent from MODIS data. *Environ. Res. Lett.* 4, Article 044003.

- Schneider, A., Friedl, M., Potere, D., 2010. Monitoring urban areas globally using MODIS 500m data: new methods and datasets based on 'urban ecoregions'. *Remote Sens. Environ.* 114, 1733–1746.
- Speak, A., Rothwell, J., Lindley, S., Smith, C., 2012. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmos. Environ.* 61, 283–293.
- van Donkelaar, A., Martin, R., Brauer, M., Kahn, R., Levy, R., Verduzco, C., Villeneuve, P., 2010. Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: develop and application. *Environ. Health Perspect.* 118, 847–855.
- van Dingenen, R., Raes, F., Putaud, J.-P., Baltensperger, U., Charron, A., Facchini, M.-C., Decesari, S., Fuzzi, S., Gehrig, R., Hansson, H.-C., 2004. A European aerosol phenomenology—1: physical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmos. Environ.* 38, 2561–2577.
- von Bismarck-Osten, C., Birmili, W., Ketzel, M., Massling, A., Petäjä, T., Weber, S., 2013. Characterization of parameters influencing the spatio-temporal variability of urban aerosol particle number size distributions in four European cities. *Atmos. Environ.* 77, 415–429.
- Wang, S., Hao, J., 2012. Air quality management in China: issues, challenges, and options. *J. Environ. Sci.* 24, 2–13.
- World Health Organization, 2005. WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide (Global Update 2005): Summary of Risk Assessment, pp. 9–11.
- Yandle, B., Vijayaraghavan, M., Bhattarai, M., 2002. The environmental kuznets curve: a primer. *PERC Res. Study* 02-1, 1–24.
- Yang, J., Yu, Q., Gong, P., 2008. Quantifying air pollution removal by green roofs in Chicago. *Atmos. Environ.* 42, 7266–7273.
- Zhao, J., Chen, S., Wang, H., Ren, Y., Du, K., Xu, W., Zheng, H., Jiang, B., 2012. Quantifying the impacts of socio-economic factors on air quality in Chinese cities from 2000 to 2009. *Environ. Pollut.* 167, 148–154.
- Zheng, J., Zhong, L., Wang, T., Louie, P., Li, Z., 2009. Ground-level ozone in the Pearl River Delta region: analysis of data from a recently established regional air quality monitoring network. *Atmos. Environ.* 44, 814–823.
- Zhu, Y., Ioannidis, J., Li, H., Jones, K., Martin, F., 2011. Understanding and harnessing the health effect of rapid urbanization in China. *Environ. Sci. Technol.* 45, 5099–5140.