Short communication

More than 500 million Chinese urban residents (14% of the global urban population) are imperiled by fine particulate hazard[☆] Chunyang He^{a, **}, Lijian Han^{b, *}, Robin Q. Zhang^c^a Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, Beijing 100875, China^b State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China^c Department of Geosciences, Murray State University, Murray, KY 42071, USA

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ABSTRACT

China's urbanization and the subsequent public vulnerability to degenerated environment is important to global public health. Among the environmental problems, fine particulate (PM_{2.5}) pollution has become a serious hazard in rapidly urbanizing China. However, quantitative information remains inadequate. We thus collected PM_{2.5} concentrations and population census records, to illustrate the spatial patterns and changes in the PM_{2.5} hazard levels in China, and to quantify public vulnerability to the hazard during 2000–2010, following the air quality standards of World Health Organization. We found that 28% (2.72 million km²) of China's territory, including 78% of cities (154 cities) with a population of >1 million, was exposed to PM_{2.5} hazard in 2010; a 15% increase (1.47 million km²) from 2000 to 2010. The hazards potentially impacted the health of 72% of the total population (942 million) in 2010, including 70% of the young (206 million) and 76% of the old (71 million). This was a significant increase from the 42% of total the population (279 million) exposed in 2000. Of the total urban residents, 76% (501 million) were affected in 2010. Along with PM_{2.5} concentration increase, massive number of rural to urban migration also contributed greatly to China's urban public health vulnerability.

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1. Introduction

China's urbanization and the subsequent public vulnerability to degenerated environmental conditions is important to global public health, because China's urbanized population is projected to account for almost 12% of the global urban population increase by 2050 (World urbanization prospects, 2014). Since the start of the "Reform and Opening-up" policy in the late 1970s, China's economy and accompanying urbanization have been growing at an unprecedented rate (Huang et al., 2014; Seinfeld, 2014). This rapid growth in a short period has led to improvements in living standards, but has also caused severe environmental pollution in areas of intense human activity (Gong et al., 2012). Especially, the heavy fine particulate (PM_{2.5}) pollution has already caused heavy haze and

increased risk to public health in densely populated areas of China (Bai et al., 2014; Han et al., 2015). Only 24 of the 350 prefectures in China had annual PM_{2.5} concentrations within the World Health Organization (WHO) air quality guidelines (AQG; 10 µg/m³), whereas 165 prefectures had annual PM_{2.5} concentrations higher than the WHO Interim Target-1 (IT-1; 35 µg/m³) based on annual averaged measurements during 2001–2006 (Han et al., 2014). These areas of high PM_{2.5} concentrations are mainly located in the east of China with a rapid increase in both the areas of high concentrations and the number of cities influenced, potentially impacting the health of the population (Gong et al., 2012; Hyslop, 2009; Lim et al., 2012). However, quantitative information remains inadequate despite its crucial importance to sustainable urban development in China. Therefore, we collected remote sensing data on PM_{2.5} concentrations (Boys et al., 2014; Van Donkelaar et al., 2015) and population census record, to illustrate the spatial patterns and changes in the PM_{2.5} hazard levels in China, and to quantify public vulnerability to the PM_{2.5} hazard during 2000–2010, following the air quality standards of WHO.

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2. Materials and methods

2.1. Materials

PM_{2.5} concentration data: We used remote sensing to estimate PM_{2.5} concentrations. An optimal estimation algorithm based on top-of-atmosphere reflectance observed by Moderate Resolution Imaging Spectroradiometer (MODIS) was developed to produce the PM_{2.5} concentration data used in the present study (Boys et al., 2014; Van Donkelaar et al., 2010). Using a simulation of the GEOS-Chem chemical transport model, PM_{2.5} concentrations were estimated from a combination of MODIS and Multi-angle Imaging SpectroRadiometer (MISR) aerosol optical depth (AOD) data with aerosol vertical profiles and scattering properties (Van Donkelaar et al., 2010; Van Donkelaar et al., 2013). The global PM_{2.5} concentration dataset had a spatial resolution of 10 km as a 3-year moving average, which was applied to reduce the uncertainty of the annual

PM_{2.5} concentration, during 1999–2011 (11; Available at: <http://fizz.phys.dal.ca/~atmos/martin/>). Moreover, the dataset was validated with ground measurement at global scale, and then significant agreement between satellite-derived estimates and ground measurements in China, outside North America and Europe, was obtained ($r = 0.81$, slope = 0.68) (Van Donkelaar et al., 2015; Van Donkelaar et al., 2010; Van Donkelaar et al., 2013). It thus provided an extensive and reasonable PM_{2.5} concentration dataset for our study at a large regional scale. In the present study, we used a subset of the global PM_{2.5} concentration dataset that covered China in 2000 and 2010.

Population records: The population records for 2000 and 2010 were obtained from the national population census reported by the National Bureau of Statistics of the People's Republic of China (available at <http://www.stats.gov.cn/tjsj/pcsj/>), and we used the total, young (age <14 years), old (age >64 years), urban, and rural populations of each prefecture.

Fig. 1. Fine particulate hazard in 2010 (a) and changes in its distribution between 2000 and 2010 (b).

Urban distribution, prefecture and province boundaries, and the regionalization system of China: We used China's urban distribution, which is the impervious surface area that observed with remote sensing technology, with a spatial resolution of 1 km to separate urban from non-urban areas for each prefecture in 2000 and 2010 (Liu et al., 2012). Prefecture and province boundaries at 1:250,000 scale were obtained from the National Geomatics Center of China (<http://ngcc.sbsm.gov.cn/>). We adopted China's most widely accepted regionalization system for the mainland: East China is the most developed area that covers Beijing, Tianjin, the Shanghai Municipalities, and Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, and Hainan Provinces; Northeast China is a traditional industrial base that covers Liaoning, Jilin and Heilongjiang Provinces; Central China is a slowly developing area that covers Shanxi, Henan, Anhui, Jiangxi, Hubei and Hunan Provinces; and West China is the least developed area that covers Chongqing Municipality, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, and Qinghai Provinces, Guangxi, Ningxia, Inner Mongolia, and the Tibet Autonomous Region (the Taiwan-Hong Kong-Macao region was not considered in this study) (Supplementary materials 4).

2.2. Methodology

Urban PM_{2.5} concentrations: The mean PM_{2.5} concentrations in urban areas were calculated based on China's urban distribution map and the China subset of the global PM_{2.5} concentrations dataset for each prefecture in both 2000 and 2010 (Han et al., 2014). To render the urban PM_{2.5} concentrations comparable between 2000 and 2010, we superimposed the urban distribution maps of 2000 and 2010 to obtain the urban and rural areas that remained constant. The PM_{2.5} concentrations in the urban areas were then

calculated based on the PM_{2.5} concentration dataset and these persistent urban areas.

PM_{2.5} hazard levels: Because China has a high level of PM_{2.5} pollution, using the air quality guideline of World Health Organization (WHO) is not sufficient to illustrate the conditions in China. We therefore use the WHO's interim target-1 (IT-1, 35 µg/m³), two fold the IT-1 (2IT-1, 70 µg/m³), and three fold the IT-1 (3IT-1, 105 µg/m³) as the standards to quantify the PM_{2.5} hazard levels and public vulnerability to PM_{2.5} hazards.

Exposure analysis: The urban PM_{2.5} concentration data along with the urban population records for each prefecture were used to calculate the urban population exposed to high air pollution levels, with PM_{2.5} concentrations higher than the WHO's IT-1 (35 µg/m³) in 2000 and 2010.

3. Result and discussion

We found that China's average PM_{2.5} concentration (28.7 µg/m³) was more than twice the global average (11.8 µg/m³) in 2010, and the increase in PM_{2.5} concentration (5.6 µg/m³) between 2000 and 2010 was nearly eightfold greater than the global average increase (0.7 µg/m³) (Supplementary materials 1). In 2010, 28% of China's territory (2.72 million km²) was exposed to high PM_{2.5} hazard levels, including 21% (2.04 million km²) exposed to PM_{2.5} hazard levels of IT-1 to twofold IT-1 (2IT-1), 7% (0.64 million km²) exposed to PM_{2.5} hazard levels of 2IT-1 to threefold IT-1 (3IT-1), and 0.4% (0.04 million km²) exposed to PM_{2.5} hazard levels of more than threefold IT-1 (>3IT-1). The high PM_{2.5} hazard levels were primarily observed in the East China Plain, including Beijing, Tianjin, south Hebei province, Henan province, Shandong province, and north Anhui and Jiangsu provinces (Fig. 1a). Such large areas with high

Fig. 2. Public vulnerability to fine particulate hazard in 2010. Total population exposed (a), young population (ages <14) exposed (b), old population (ages >64) exposed (c), and urban population exposed (d).

PM_{2.5} hazard levels represent a significant increase during 2000–2010. More than 15% of China's territory (1.47 million km²) showed increased PM_{2.5} concentrations, including 10% of China's territory changing from <IT-1 to >IT-1 and 6% of China's territory with >IT-1 levels in 2000 worsening by 2010. The deteriorating areas were mainly located in Beijing, Tianjin, southern Hebei Province, and central and western Shandong Province. The newly added areas exposed to PM_{2.5} hazard that changed from <IT-1 to >IT-1 were mainly found in west Liaoning province, east Shandong province, Guangdong and Guangxi provinces (Fig. 1b). In 2010, 78% of large cities with populations greater than 1 million (154 cities) were exposed to high PM_{2.5} hazard levels, including 38% (76 cities), 35% (70 cities), and 4% (8 cities) with PM_{2.5} hazard levels of IT-1 to 2IT-1, 2IT-1 to 3IT-1, and >3IT-1, respectively. Eight cities in East and Central China were exposed to the highest PM_{2.5} hazard levels of >3IT-1: Shijiazhuang, Xingtai, and Handan in Hebei province and Heze in Shandong province in East China, and Zhengzhou, Luoyang, Anyang, and Kaifeng in Henan province in Central China. All six

large cities with a population greater than 10 million (Beijing, Shanghai, Tianjin, Chongqing, Guangzhou, and Shenzhen) were exposed to high PM_{2.5} hazard levels (>IT-1).

We also found that the heavy PM_{2.5} hazards have already impacted the health of Chinese population (Fig. 2a). In 2010, 72% of the total population (942 million) was exposed to the high PM_{2.5} hazard levels, mainly those living in East (29% of the total population, 378 million) and Central China (26% of the total population, 341 million). Some research findings suggested that old and young members of the population are more susceptible, showing increased hospitalization and mortality (Gouveia and Fletcher, 2000; Brunekreef and Holgate, 2002). In addition, we discovered that 70% of the young population (ages <14; 206 million) were exposed to the high PM_{2.5} hazard levels, including 72 million in East China, 83 million in Central China, and 44 million in West China. The main area of impact for the young population is in the East China Plain, with the largest effect in the northern part of Henan province (Fig. 2b). Furthermore, 76% of the old population (ages

Fig. 3. Urban (a) and rural (b) population changes between 2000 and 2010.

>64; 71 million) were exposed to the high PM_{2.5} hazard levels, including 31 million in East China, 24 million in Central China, and 13 million in West China. The exposed seniors were densely distributed in the East China Plain. Six large cities, Shanghai, Beijing, Tianjin, and Suzhou in East China, Chongqing and Chengdu in West China, accounted for 14% (10 million) of the affected seniors (Fig. 2c). The rapid increase of 21% total population (279 million) between 2000 and 2010 contributed to this rapid increase in public vulnerability to increased PM_{2.5} hazard. From 2000 to 2010, we found a further 97 million of the young population became vulnerable. Thirty-four million young people in East China, 37 million in Central China, and 18 million in West China experienced increased exposure. Eight million more seniors have been exposed between 2000 and 2010, including increases of six million, three million, and one million in East, Northeast and Central China, and a decrease of two million in West China.

We also investigated the vulnerability of the urban population to PM_{2.5} hazard. We found that 76% of the total urban population (501 million) was affected by the PM_{2.5} hazard in 2010 (Fig. 2d), with 237 million in East China and 149 million in Central China. Moreover, five large cities (Shanghai, Beijing, Chongqing, Tianjin, and Guangzhou) accounted for 15% (73 million) of the total affected urban population in 2010. We found a notable increase of 21% of the urban population (278 million) exposed to PM_{2.5} hazard between 2000 and 2010. Moreover, population increases in large cities contributed a large proportion to the exposed urban population. For instance, 15% (51 cities) of large cities with a population >1 million accounted for 35% of the total increase (97 million) in the urban population subjected to increased health risks due to PM_{2.5} hazard in China. The population of five megacities with a population >10 million (Beijing, Shanghai, Guangzhou, Tianjin, and Chongqing) accounted for 8% of the total increased urban population (23 million) exposed to PM_{2.5} hazard.

Urbanization is considered as one of the engines of modernization and economic growth, and is serving an important role in achieving China's urban dream (Bai et al., 2014). In March 2014, the Chinese central government released the National New-type Urbanization Plan, which sets targets for the proportion of China's urban population to rise from 52% in 2012 to 60% by 2020 (Bai et al., 2014). However, along with the increase in PM_{2.5} concentrations, we found that mass population migration induced by rapid urbanization also contributed extensively to urban public health vulnerability in China. Rural population decreased by 116 million while urban population increased by 210 million from 2000 to 2010. The change was particularly significant in East and Central China (Fig. 3a, b). In areas with PM_{2.5} hazard in 2010, we estimated that 2–21% of the increased urban population that affected by PM_{2.5} hazard was the result of natural urban population increase, but 79–98% of the increase was attributed to rural-to-urban migration (Supplementary Materials 2). Meanwhile, the affected rural population decreased by 101 million, from 585 million in 2000 to 484 million in 2010. In megacities such as Beijing, Shanghai, Tianjin, and Chongqing, the urban population increased from three to six million (Supplementary Materials 3). The vast majority of the rural population decrease resulted from migration to urban areas was induced by rapid urbanization. This differs from

the previous perception that most of the increase in hazard exposure was driven by increases in PM_{2.5} concentration rather than changes in population due to migration (Van Donkelaar et al., 2015).

We argue that both the Chinese government and the public should pay more attention to environmental protection as rapid urbanization progresses over the next decade. We suggest that the control and reduction of air pollutant emission in megacities in East and Central China should be implemented rapidly and effectively. We urge that the active participation of the public in reducing air pollution as urbanization progresses should be further encouraged and supported. We believe that the “Win-win” cooperation of the government and the public to mitigate the PM_{2.5} hazard would ensure a sustainable future while accomplishing China's dream of urbanization.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.envpol.2016.07.038>.

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