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Global population exposed to fine particulate pollution by population increase and pollution expansion

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Abstract Ambient fine particulate ($PM_{2.5}$) pollution threatens public health. Previous studies have primarily focused on $PM_{2.5}$ estimation, with the quantitative analysis of public exposure and the reason for increased risk receiving limited attention. Quantitative information is essential for environmental risk estimation. Thus, we collected $PM_{2.5}$ data and population records to illustrate the spatiotemporal patterns of $PM_{2.5}$ pollution and to quantify public vulnerability and the cause of increased exposure at global, regional, and country scales from 2000 to 2010, following the air quality standards of the World Health Organization. We found that 11.0×10^6 km^2 (8%) of the global terrestrial area was exposed to $PM_{2.5}$ pollution (> 35 μg/m^3) in 2010, an addition of 4.3×10^6 km^2 since 2000. Furthermore, by 2010, 1.94 billion (30%) people worldwide were exposed to $PM_{2.5}$ pollution, including 966 and 778 million in Eastern and Southern Asia, respectively, comprising 962 million in China and 543 million in India. After 2000, the vulnerability of 698 million people to $PM_{2.5}$ pollution increased, including 356 and 280 million in Southern and Eastern Asia, respectively, accounting for 279 million in China and 253 million in India. Moreover, 25% of the global vulnerability increase was from local population growth, and 75% was due to pollution expansion. Specifically, 26 and 16% of the increase in public vulnerability in Southern and Eastern Asia (22 and 16% in India and China), respectively, were from local population growth. We suggest that countries in which migration has contributed to an increase in public vulnerability should balance pollutant emission reduction and migration control to reduce vulnerability. In addition, cooperation between the government and public could help mitigate global pollution as well as environmental and human health risks.

Keywords Air quality · Public health · Global · Continental · $PM_{2.5}$

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Introduction

Ambient fine particulate ($PM_{2.5}$) matter is small in diameter (≤ 2.5 μm) and can be emitted directly or formed secondarily in the atmosphere, thus carrying considerable risk to public health (Brauer et al. 2012; Huang et al. 2014; Lim et al. 2012). Exposure to ambient $PM_{2.5}$ pollution is associated with an increase in cardiovascular and circulatory diseases, lower respiratory infection, chronic respiratory diseases, and even cancers (Lim et al. 2012; Du and Li 2016). Many high-income countries have established monitoring networks for $PM_{2.5}$ detection; however, few low- and mid-income countries have created monitoring networks. Those networks have limited spatial distribution, making it difficult to quantitatively illustrate the spatial pattern of $PM_{2.5}$ concentration at global or regional scales (Han et al. 2014; Deary et al. 2016). Remote sensing estimations of $PM_{2.5}$ concentrations provide an efficient way to understand public vulnerability to such pollution, because the ground measurements are majorly available at limited urban areas in recent years (van Donkelaar et al. 2010; Boys et al. 2014; van Donkelaar et al. 2015a). Previous research has focused on $PM_{2.5}$ concentration estimation using remote sensing technology but paid little attention to public exposure analysis (Boys et al. 2014; van Donkelaar et al. 2015a; Han et al. 2015a; Peng et al. 2016). This lack in quantitative estimation of what drives increased exposure has resulted in the belief that increases (or decreases) in exposure are triggered by changes in $PM_{2.5}$ rather than changes in the population itself (van Donkelaar et al. 2015a). However, quantitative information is important to global regions and countries when estimating environmental risk. Therefore, we collected remote sensing data (van Donkelaar et al. 2015a, b) on $PM_{2.5}$ concentrations and gridded population records (CIESIN 2005; CIESIN 2005) to illustrate the spatial pattern changes in $PM_{2.5}$ pollution levels, quantify public vulnerability to $PM_{2.5}$ pollution, and quantify the contributions of population increase and pollution expansion to increased public vulnerability at global, regional, and country scales from 2000 to 2010, following the air quality standards of the World Health Organization (WHO).

Materials and methods

Materials

The Global Annual $PM_{2.5}$ Grids dataset represents a series of 3-year running mean grids (1998–2012) of $PM_{2.5}$ data derived from a combination of MODIS (Moderate Resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging SpectroRadiometer), and SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) Aerosol Optical Depth (AOD) satellite retrievals (van Donkelaar et al. 2015a, b). The dataset showed strong agreement ($r = 0.81$; slope = 0.68) with ground-based measurements and was thus adopted for global study of $PM_{2.5}$ concentration dynamics. It was a 3-year running average record to reduce error for each single year. For instance, $PM_{2.5}$ in 2000 was an average of the $PM_{2.5}$ in 1999, 2000, and 2001. The dataset have spatial resolution of 0.1 degree (or ~ 10 km). The dataset is available at the Socioeconomic Data and Applications Center (SEDAC) at Columbia University (http://sedac.ciesin.columbia.edu/). We used the global $PM_{2.5}$ concentration in 2000 and 2010 for this research.

Population records in 2000 were obtained from the Gridded Population of the World Version 3 (GPWv3) (CIESIN 2005) and in 2010 were obtained from the Gridded Population of the World: Future Estimates (GPWFE) (CIESIN 2005). These data are at 2.5 arc-minutes (or ~ 5 km) resolution and therefore could matched the $PM_{2.5}$ dataset for population exposure analysis. These data were downloaded from SEDAC at Columbia University (http://sedac.ciesin.columbia.edu/).

The United Nations' global map was used and included global sub-regions and countries (Fig. S1).

Method of data analysis and collection

$PM_{2.5}$ pollution levels

The World Health Organization (WHO) sets the air quality guideline (AQG) of annual $PM_{2.5}$ concentration as 10 μg/m^3, which is the lowest levels at which total, cardiopulmonary and lung cancer mortalities have been shown to increase with more than 95% confidence in response to long-term exposure to $PM_{2.5}$. In WHO's standard, the highest level of annual $PM_{2.5}$ concentration is 35 μg/m^3 (interim target-1 (IT-1)), which is associated with about a 15% higher long-term mortality risk relative to the AQG level (WHO 2005). Because the global $PM_{2.5}$ concentration has a range of more than 100 μg/m^3, which is beyond the AQG of WHO, thus we used the WHO's IT-1, twofold IT-1 (2IT-1, 70 μg/m^3), and threefold IT-1 (3IT-1, 105 μg/m^3) as the standards to quantify $PM_{2.5}$ pollution levels and public vulnerability.

Exposure analysis

Global $PM_{2.5}$ concentrations and populations were used to calculate the population exposed to $PM_{2.5}$ pollution (concentration ≥ 35 μg/m^3) at the global, global sub-regional, and national levels in 2000 and 2010. Increased population exposure due to local population change was calculated as the population changes in areas in which the $PM_{2.5}$ concentration was greater than 35 μg/m^3 in both 2000 and 2010. Increased population exposure due to $PM_{2.5}$ pollution expansion was determined in areas in which the $PM_{2.5}$ concentration was greater than 35 μg/m^3 in 2010, but less than 35 μg/m^3 in 2000.

Results and discussion

Global average $PM_{2.5}$ concentration increased from 11.1 μg/m^3 in 2000 to 11.8 μg/m^3 in 2010. In 2010, 8% of the global terrestrial area (11.0×10^6 km^2) was exposed to $PM_{2.5}$ pollution (> 35 μg/m^3) and was mainly located at Eastern Asia (2.7×10^6 km^2), Western Africa (2.4×10^6 km^2), Western Asia (2.0×10^6 km^2), Northern Africa (1.8×10^6 km^2), and Southern Asia (1.7×10^6 km^2), as well as particularly in Eastern Asia with 0.4×10^6 and 0.6×10^6 km^2 exposed to > 3IT-1 and 2IT-1 to 3IT-1, respectively (Fig. 1a; Fig. S2). Among these regions, seven countries with more than 0.5×10^6 km^2 exposed to $PM_{2.5}$ pollution included China (2.7×10^6 km^2), Saudi Arabia (1.1×10^6 km^2), India (0.8×10^6 km^2), Mauritania (0.6×10^6 km^2), Niger

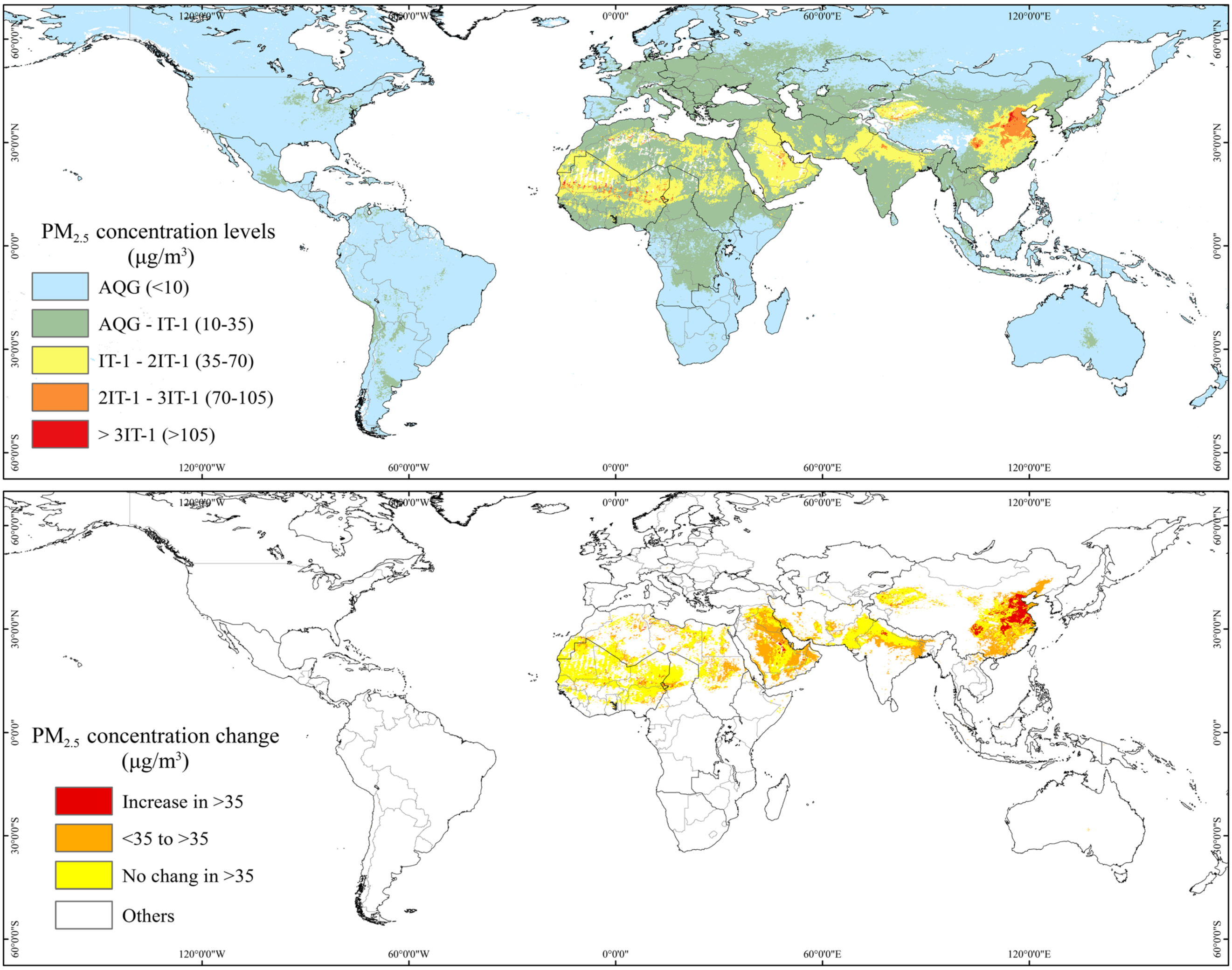

Fig. 1 Global $PM_{2.5}$ pollution in 2010 (**a**) and changes in its distribution from 2000 to 2010 (**b**)

(0.6×10^6 km^2), Mali (0.5×10^6 km^2), and Algeria (0.5×10^6 km^2). Moreover, 12 countries had more than half of their terrestrial area exposed to $PM_{2.5}$ pollution, including Bahrain 100%), Kuwait (100%), United Arab Emirates (99%), Qatar (95%), Iraq (88%), Mauritania (84%), Saudi Arabia (72%), Western Sahara (72%), Pakistan (68%), Niger (63%), Mali (54%), and Senegal (51%). Such large areas with high $PM_{2.5}$ pollution levels represent a significant increase from 2000 to 2010 (Table S1). In addition, an increase of 3.3% of the global terrestrial area (4.3×10^6 km^2) was exposed to $PM_{2.5}$ pollution from 2000 to 2010 (Fig. 1b; Fig. S1). Four regions showed an increase of more than 0.5×10^6 km^2: Eastern Asia (1.5×10^6 km^2), Western Asia (1.3×10^6 km^2), Southern Asia (0.7×10^6 km^2), and Northern Africa (0.6×10^6 km^2). Among these regions, China saw an increase of 1.5×10^6 km^2 and Saudi Arabia an increase of 0.7×10^6 km^2 exposed to $PM_{2.5}$. Moreover, five countries experienced an increase in exposure of more than half of their terrestrial area, including Bahrain (100%), Kuwait (92.5%), United Arab Emirates (82%), Qatar (73%), and Iraq (50%) (Table S2).

We have found that $PM_{2.5}$ has potentially influenced the health of global population due to the exposure (Fig. 2; Fig. S3). In 2010, 30% of the global population (1.94 billion) was exposed to $PM_{2.5}$ pollution, including 62% of people from Eastern Asia (966 million), 47% of people from Southern Asia (778 million), 30% of people from Western Africa (86 million), 28% of people from Western Asia (62 million), and 18% of people from Northern Africa (32 million). We also determined that China (962 million; 72% of its total population), India (543 million; 48% of its total population), Pakistan (153 million; 87% of its total population), Bangladesh (52 million; 31% of its total population), and Nigeria (50 million; 35% of its total population) have 50 million people or more exposed to $PM_{2.5}$ pollution. The rapid global increase of 698 million people exposed to $PM_{2.5}$ between 2000 and 2010 has contributed to considerable vulnerability of the public to $PM_{2.5}$ pollution in 2010 (Fig. S4),

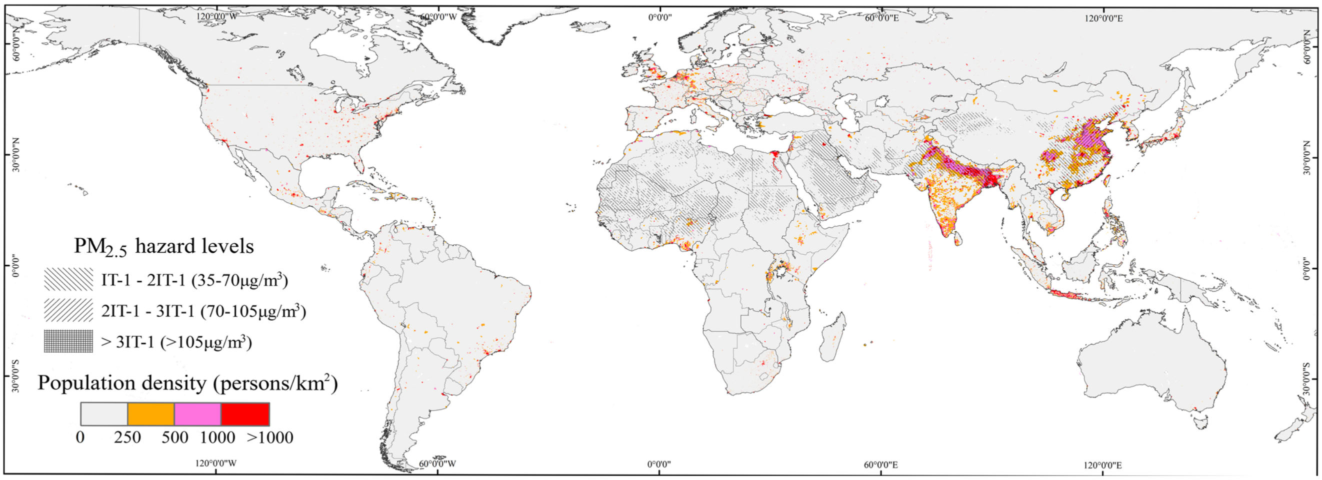

Fig. 2 Public vulnerability to $PM_{2.5}$ pollution in 2010

including a 356 million increase in Southern Asia, 280 million increase in Eastern Asia, 35 million increase in Western Asia, and 14 million increase in Northern Africa. Moreover, six countries have seen an increase of more than 10 million people between 2000 and 2010, accounting for 93% of the global total increase (650 million), and include China (279 million increase), India (253 million increase), Bangladesh (51 million increase), Pakistan (36 million increase), Iraq (16 million increase), and Saudi Arabia (13 million increase).

Expansion in $PM_{2.5}$ pollution is considered the major reason for the substantial increase in public vulnerability. We further analyzed the proportion of increased population exposure due to local population increase and due to $PM_{2.5}$ pollution expansion. We found that 25% of the increase in global population exposure was due to local population increase, and 75% was due to $PM_{2.5}$ pollution expansion (Fig. 3a). However, these contributions varied markedly among regions. All increased population exposure in Western Africa was due to local population increase, whereas all increased population exposure in Australia, New Zealand, Central America, Central Asia, Melanesia, Northern America, Northern Europe, South America, Southern Africa, and Southern Europe was due to $PM_{2.5}$ pollution expansion. Moreover, 88 and 12% of increased population exposure in Middle Africa, 56 and 44% in Western Europe, 52 and 48% in Northern Africa, 26 and 74% in Southern Asia, 26 and 74% in Eastern Africa, 19 and 81% in Western Asia, 16 and 84% in Eastern Asia, 5 and 95% in South-Eastern Asia, 5 and 95% in Eastern Europe, and 4 and 96% in the Caribbean were from local population increase and $PM_{2.5}$ pollution expansion, respectively. Among these regions (Fig. 3b), the increase in population exposure in seven countries was due to local population increase, including Cameroon, Mali, Mauritania, Nigeria, Senegal, Western Sahara, and Burkina Faso. Furthermore, the increase in public vulnerability in 43 countries was due to local population growth; for example, the 91% (33 million), 22% (55 million), and 16% (43 million) increase in public vulnerability observed in Pakistan, India, and China, respectively. Increased public vulnerability in the remaining countries was due to $PM_{2.5}$ pollution expansion.

Urbanization in developing countries (e.g., China and India) is the major cause of population migrations. Cities, as the major source areas of $PM_{2.5}$ pollution in many developing counties, are the destination of most domestic migrants (Han et al. 2015a, b; Cohen 2006). Thus, rapid and unplanned urbanization in developing countries can increase population exposure to $PM_{2.5}$ pollution and contribute considerably to the burden of health expenditure (Gong et al. 2012). Some large developing countries (e.g., China) are now attempting to undertake rapid urbanization with strong attention to environmental protection. However, China still suffers from heavy $PM_{2.5}$ pollution due to its previous rapid development in which economic growth was the focus (Han et al. 2015c; Bai et al. 2014). Thus, we suggest that countries in which migration contributes to a relatively large proportion of increased public vulnerability should balance pollutant emission reduction and migration control to reduce vulnerability and exposure (e.g., countries listed in Fig. 3).

Both the government and the public in developing countries suffering significant $PM_{2.5}$ pollution should pay more attention to environmental protection as well as the intensive human activities (e.g., urbanization, industrialization) that will take place over the next decades. Control of and reduction in air pollution emissions in Eastern China and Northern India, where pollution is highly attributed to increasing human activities, and ecological protection in areas such as Northern Africa and the Middle East, where pollution is highly attributed to natural emissions, which must be taken into consideration and action. Mass population migration from no or low pollution areas to heavy pollution areas should be discouraged or controlled until the risk declines to reduce both health hazard and health expenditure. Cooperation between the

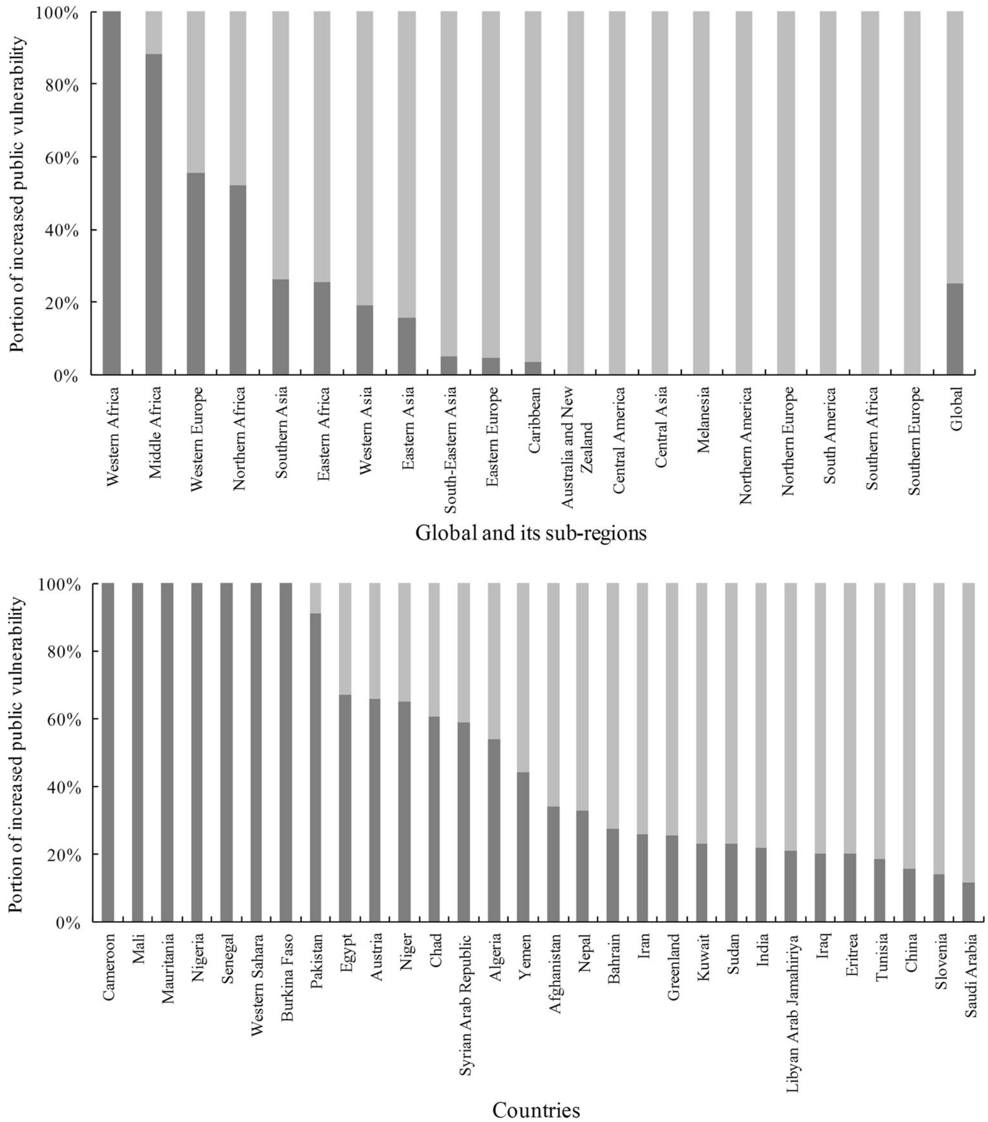

Fig. 3 Increased public vulnerability related to local population increase (dark gray bars) and $PM_{2.5}$ pollution expansion (light gray bars) at global, regional (**a**), and country (**b**) scales

government and public could go a long way to ensure an environmentally sustainable and ecological civilization.

Conclusions

Ambient fine particulate pollution threatens public health. Previous research has focused on $PM_{2.5}$ estimation, with limited attention given to the quantitative analysis of public exposure or reasons for the increased risk. Such quantitative information is essential for environmental risk estimation. We collected $PM_{2.5}$ data and population records to illustrate the spatiotemporal patterns of $PM_{2.5}$ pollution and to quantify public vulnerability and the causes of increased vulnerability at the global, regional, and country scales from 2000 to 2010.

1) Global small areas exposed to $PM_{2.5}$ pollution but with large portion of global population. We found that 11.0×10^6 km^2 (8%) of global terrestrial area was exposed to $PM_{2.5}$ pollution (> 35 μg/m^3) in 2010, an addition of 4.3×10^6 km^2 since 2000. In 2010, 1.94 billion (30%) people worldwide were exposed to $PM_{2.5}$ pollution, including 966 and 778 million in Eastern and Southern Asia, respectively, accounting for 962 million in China and 543 million in India. After 2000, 698 million more people were vulnerable to exposure, including 356 and 280 million in Southern and Eastern Asia, respectively, consisting of 279 million in China and 253 million in India.
2) Population increase contributing a meaningful amount to the global population exposure to $PM_{2.5}$ pollution. Twenty-five percent of the increase in global vulnerability was from local population increase, where 75% was due to pollution expansion. In Southern and Eastern Asia, 26 and 16% of the increase in public vulnerability (22 and 16% in India and China) were from local population

growth. Thus, countries in which migration has contributed to an increase in public vulnerability should balance pollutant emission reduction and migration control to reduce public vulnerability. Furthermore, strong cooperation between the government and public could help mitigate pollution and its associated environmental and human health risks.

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