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Spatial and temporal trends in the mortality burden of air pollution in China: 2004–2012

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ABSTRACT

While recent assessments have quantified the burden of air pollution at the national scale in China, air quality managers would benefit from assessments that disaggregate health impacts over regions and over time. We took advantage of a new 10 × 10 km satellite-based $PM_{2.5}$ dataset to analyze spatial and temporal trends of air pollution health impacts in China, from 2004 to 2012. Results showed that national $PM_{2.5}$ related deaths from stroke, ischemic heart disease and lung cancer increased from approximately 800,000 cases in 2004 to over 1.2 million cases in 2012. The health burden exhibited strong spatial variations, with high attributable deaths concentrated in regions including the Beijing–Tianjin Metropolitan Region, Yangtze River Delta, Pearl River Delta, Sichuan Basin, Shandong, Wuhan Metropolitan Region, Changsha–Zhuzhou–Xiangtan, Henan, and Anhui, which have heavy air pollution, high population density, or both. Increasing trends were found in most provinces, but with varied growth rates. While there was some evidence for improving air quality in recent years, this was offset somewhat by the countervailing influences of in–migration together with population growth. We recommend that priority areas for future national air pollution control policies be adjusted to better reflect the spatial hotspots of health burdens. Satellite-based exposure and health impact assessments can be a useful tool for tracking progress on both air quality and population health burden reductions.

1. Introduction

Over recent decades, rapid economic development has led to worsening air quality in China (Wang et al., 2014; Wu et al., 2012; Zhao et al., 2013a, b), which now ranks as one of the most polluted countries in the world (Van Donkelaar et al., 2010; Verstraeten et al., 2015). As a leading modifiable risk factor for non–communicable diseases, air pollution has attracted considerable interest from both the research and policy communities (Krewski et al., 2009; Laden et al., 2006; Pope et al., 2009; Pope and Dockery, 2006; Shang et al., 2013; West et al., 2016; Yang et al., 2013). However, assessments of health impacts, and their trends over time and space, have been hampered by the limited availability of relevant air monitoring prior to 2013 in China. Initial health impact studies used surrogate measures such as ambient PM_{10} concentrations measured at fixed monitoring stations to estimate health outcomes attributable to China's air pollution (Cheng et al., 2013; Hou et al., 2012; Matus et al., 2012; Zhang et al., 2008). However, PM_{10} is a less robust health–related exposure metric than $PM_{2.5}$ (USEPA, 2012), and central–site monitoring data may lead to exposure uncertainty related to spatial variability of PM, population density and demographic characteristics (Steinle et al., 2013).

In recent years, methods have been developed for estimating ground–level $PM_{2.5}$ concentrations based on satellite derived aerosol optical depth (AOD), providing a promising alternative for estimating exposure to outdoor $PM_{2.5}$ and associated health impacts, with more extensive spatial and temporal coverage (Brauer et al., 2012, 2015; Ma et al., 2014; Yao and Lu, 2014). For example, taking advantage of a global $PM_{2.5}$ dataset derived from AOD, the Global Burden of Disease (GBD) project reported that outdoor air pollution in China caused 1.2 million premature deaths and 25 million disability adjusted life years (DALY) losses in 2010 (Yang et al., 2013). A subsequent study reported a lower mortality burden of 0.35–0.50 million premature deaths, based on a different exposure methodology (Chen et al., 2013a). Both of these $PM_{2.5}$-based health assessments reported results only for a single year and for China as a whole.

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Recently, as the Chinese government's demands for air quality management broadened from understanding the scope of the problem to targeting interventions, identification of spatial and temporal trends in health burdens attributable to air pollution is becoming more and more important. A recent study evaluated the temporal trend and spatial distributions of PM_{10}–related health impacts in China based on monitoring data from 2001 to 2011, contributing valuable insights into this question (Cheng et al., 2013). However, because PM_{10} trends may not track those of $PM_{2.5}$, spatial and temporal trends derived from PM_{10} data can be misleading (Cheng et al., 2013; Ma et al., 2016). Therefore, more accurate and refined information of the spatial–temporal characteristics of $PM_{2.5}$ effects are needed to support future policy interventions.

To address this need, we used a new 10 km resolution satellite derived $PM_{2.5}$ dataset in conjunction with fine scale population data to develop novel estimates of $PM_{2.5}$ related health damage in China from 2004 to 2012 at the subnational scale (Burnett et al., 2014; Ma et al., 2016; Yang et al., 2009). The implications of observed temporal trends and spatial distributions of impacts for future policy directions are explored.

2. Methods and data

While several air pollutants are known to have adverse health impacts, we focus here on outdoor $PM_{2.5}$ as the indicator of risk as it is widely regarded as the single best metric of air pollution–related risk to public health (USEPA, 2012). Regarding outcomes, we selected the premature deaths caused by stroke (International Classification of Diseases Revision 10 codes/ICD-10: I60–I69), ischemic heart disease (IHD, ICD-10: I20–I25), and lung cancer (LC, ICD-10: C33–C34) because of strong evidence for causal effects between these outcomes and $PM_{2.5}$ from prior high–quality epidemiological studies and sufficient cause-specific mortality data to estimate outcome–specific effect sizes per unit of exposure (Burnett et al., 2014; NHFPCC, 2005–2013). We excluded chronic obstructive pulmonary disease (COPD) deaths because the mortality data for COPD were not available. Annual cause-specific baseline mortality rates were taken from the China Health Statistical Yearbook.

Population weighted exposure (PWE) to $PM_{2.5}$ was calculated using $PM_{2.5}$ concentrations derived from satellite AOD at 10 km resolution and population distribution maps at 1 km resolution (Ma et al., 2016; Yang et al., 2009). Briefly, we developed and validated a model for estimating $PM_{2.5}$ based on collection 6 AOD retrieved by the US National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS), meteorology data, land use data and China's ground-monitoring $PM_{2.5}$ data in 2013. Historical daily $PM_{2.5}$ concentrations (2004–2012) were then estimated with this model using historical AOD data as inputs, assuming that the daily relationship between $PM_{2.5}$ and AOD was constant for the same Day of Year (DOY) in each year. This model was calibrated to minimize bias in the monthly and seasonal estimates on $PM_{2.5}$ and has been successfully applied in recent analyses (Chen et al., 2016; Liu et al., 2016b; Ma et al., 2016). The population distribution maps we adopted in this study also have been successfully applied in prior studies (Huang et al., 2014; Liu et al., 2013). In regard to relative risk per unit of exposure for each mortality outcome, the ideal one for the study population should be the results from Chinese cohort studies. However, to our knowledge, there are no published Chinese cohort studies directly examining the impacts of $PM_{2.5}$ on mortality so far. Most of existing Chinese cohort studies used the concentrations of SO_2, NO_2, TSP, or PM_{10} as exposure surrogates, which were poorer predictors of mortality compared with $PM_{2.5}$ (Cao et al., 2011; Liu et al., 2016a; Zeng et al., 2016; Zhou et al., 2014). In the few published $PM_{2.5}$ cohort studies (Guo et al., 2016; Qian et al., 2016), only the impacts of $PM_{2.5}$ on lung cancer incidence and preterm birth are discussed. Under this circumstance, the integrated exposure response (IER) model developed as part of the GBD study seems to be the most suitable choice for the estimates of mortality burdens attributable to $PM_{2.5}$ in China. Even compared with the RRs estimated based on Chinese TSP cohort and the conversion rate of $PM_{2.5}$/TSP, the RRs evaluated by the IER model can yield sensible results in the risk analysis over the range of concentrations that prevail in China (Burnett et al., 2014). 5 μg/m^3 of annual $PM_{2.5}$ was assumed as the counterfactual theoretical–minimum–risk exposure (Burnett et al., 2014). It should be noted that because the IER model was developed for adults, the age ranges for population and baseline incidence rates used in existing studies using the IER model are usually aged 25 and over or aged 30 and over (Lelieveld et al., 2015; Silva et al., 2016). However, the data of population and cause-specific baseline incidence rates with detailed age structures are not available in China at such a long time scale and fine spatial resolution. So we used the aggregated all-age data for population and baseline incidence rates in this study. While this might induce some bias, we think the biases are acceptable because most of baseline mortalities from IHD, stroke and lung cancer occur among adults (NHFPCC, 2005–2013). Using these inputs, we computed annual excess deaths attributable to outdoor $PM_{2.5}$ exposure as follows (Cheng et al., 2013; Zhang et al., 2008).

$$ED_{i,j,t} = \left(1 - \frac{1}{RR_{i,j,t}}\right) * I_{i,j,t} * P_{i,j,t} = AF_{i,j,t} * I_{i,j,t} * P_{i,j,t}$$

where $ED_{i,j,t}$ is the excess deaths caused by air pollution for stroke, IHD or LC; $AF_{i,j,t}$ is the attributable fraction (AF), defined as the fraction of the disease burden attributable to $PM_{2.5}$;$I_{i,j,t}$ is the annual all-age incidence rate of the mortality end point, obtained from China Health Statistical Yearbook (2005–2013) compiled by the Ministry of Health of China according to ICD-10 codes (NHFPCC, 2005–2013); $P_{i,j,t}$ is the permanent all-age population aggregated from population density map at 1 km resolution provided by Chinese Academy of Science (Yang et al., 2009); $RR_{i,j,t}$ is the relative risk of premature mortality due to $PM_{2.5}$ obtained from the integrated exposure response (IER) model (Burnett et al., 2014) and *i*, *j*, and *t* are the grid, the prefecture and the year, respectively. Annual excess deaths caused by air pollution were estimated at 10 km resolution and also aggregated for 339 prefectures, 31 provinces and the whole of China, for each year from 2004 to 2012.

3. Results

During the period 2004–2012, over 93% of people in China lived in areas where $PM_{2.5}$ exceeded China's National Air Quality Standard for GradeII of 35 μg/m^3 (Fig. 1). Population weighted exposure (PWE) averaged between 67.1 and 76.7 μg/m^3 for China as a whole (Table S1). To visualize how regional impacts of $PM_{2.5}$ are distributed across the concentration range, we plot the distribution of population as a function of ambient $PM_{2.5}$ in 2004 (Fig. 1A) and 2012 (Fig. 1B). The distributions were bimodal, with one peak in the range 45–60 μg/m^3 and another around 80 μg/m^3. Compared with 2004, the population exposure shifted to greater extremes of $PM_{2.5}$ concentrations in 2012.

Total excess premature deaths due to stroke, IHD, and LC attributable to outdoor $PM_{2.5}$ exposure in China increased rapidly from 807 (95% CI: 328–1057) thousand cases in 2004 to 1250 (95% CI: 559–1672) thousand cases in 2012. Specifically, excess deaths due to stroke, IHD, and LC increased from 589 (95% CI: 209–736), 124 (95% CI: 86–194) and 93 (95% CI: 33–127) thousand cases in 2004 to 761 (95% CI: 274–947), 321 (95% CI: 224–498) and 169 (95% CI: 61–227) thousand cases in 2012 (Fig. 2), with the annual average growth rate of 3.25%, 12.63%, and 7.75%, respectively. In 2012, 43.9%, 29.0% and 27.9% of deaths caused by stroke, IHD and LC, respectively, in China were attributed to exposure to outdoor $PM_{2.5}$.

At the provincial level, the highest ambient $PM_{2.5}$ concentrations were observed in the Beijing–Tianjin Metropolitan Region, Henan, and Shandong, with PWEs of 102.4, 107.0, and 101.1 μg/m^3 in 2012,