Environment International 98 (2017) 160–170

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

Assessment of health burden caused by particulate matter in southern China using high-resolution satellite observation

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ARTICLE INFO

Article history:
Received 10 June 2016
Received in revised form 2 November 2016
Accepted 3 November 2016
Available online 10 November 2016

Keywords:
Satellite
PM_{10}
$PM_{2.5}$
C-R function
Health
Urbanization

ABSTRACT

As the major engine of economic growth in China, the Pearl River Delta (PRD) region is one of the most urbanized regions in the world. Rapid development has brought great wealth to its citizens; however, at the same time, increasing emissions of ambient pollutants from vehicles and industrial combustions have caused considerable air pollution and negative health effects for the region's residents. In this study, the concentration response function method was applied together with satellite-retrieved particulate matter (PM_{10} and $PM_{2.5}$) concentration data to estimate the health burden caused by this pollutant from 2004 to 2013. The value of statistical life was used to calculate the economic loss due to the negative health effects of particulate matter pollution. Our results show that in the whole PRD region, the estimated number of deaths from the four diseases attributable to $PM_{2.5}$ was the highest in 2012, at 45,000 (19,000–61,000); the number of all-cause hospital admissions due to PM_{10} was the highest in 2013, reaching up to 91,000 (0–270,000) (excluding Hong Kong). Among the 10 cities, the capital city Guangzhou suffered the most from ambient particulate matter pollution and had the highest mortality and morbidity over the 10 years. The cost of mortality in this region was the highest in 2012, at 46,000 million USD, or around 6.1% of local total gross domestic product (GDP). The positive spatial relationship between the degree of urbanization and the particulate matter concentration proves that the urbanization process does worsen air quality and hence increases the health risks of local urban citizens. It is recommended that local governments further enhance their control policies to better guarantee the health and wealth benefits of local residents.

1. Introduction

Since the implementation of China's open policy, the Pearl River Delta (PRD) region has experienced rapid economic growth and accelerated urbanization (Lu et al., 2013). At the same time, however, these dramatic processes have led to serious and complex air quality issues in this region (Zhong et al., 2013). Inhalable coarse particulate matter with aerodynamic diameter less than 10 μm (PM_{10}) and fine particulate matter with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) are the two types of small particles of interest in this study. The burning and consumption of fossil fuels have released substantial amounts of SO_2 and NO_x into the atmosphere. A series of oxidation processes can transform SO_2 and NO_x into sulfate and nitrate particles (Limbeck et al., 2003). In addition to sulfate and nitrate particulates, other particle components from both natural and anthropogenic processes include elemental carbon, secondary organic aerosol, metals, crustal metal, and sea salt (Huang et al., 2014; Louie et al., 2005). However, in the PRD region, secondary sulfate and secondary nitrate are the dominant components of the particulate matter (Huang et al., 2009; Yuan et al., 2006), which demonstrates that anthropogenic processes are the major contributors of aerosol loading over this region.

Particulate matter influences human living conditions in several ways, such as reducing visibility and causing acid deposition (Lu et al., 2015). Therefore, in the past 10 years, many studies (observational analyses and model simulations) of ambient particulate matter pollution have been carried out in this region, and each has made great contributions to the control and understanding of this notorious pollution issue from both scientific and policy aspects. For example, Wu et al. (2013) applied the Comprehensive Air Quality Model with Extensions (CAMx) to study the sources of fine particulate matter in the 10 cities of the PRD region. Their results indicated that mobile emissions and super-regional sources (i.e., those outside the PRD region) are the two dominant contributors to $PM_{2.5}$ in this area. Liu et al. (2013) used model simulation to analyze the manner in which the concentration of ambient particulate matter responded to a reduction of emissions in this region. Their results showed that an abatement strategy for the

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http://dx.doi.org/10.1016/j.envint.2016.11.002
0160-4120/

reduction of fine particulate matter would be complicated and extensive. Yao et al. (2014) applied CAMx to analyze particulate matter transportation and transformation on hazy days and showed that the complex terrain in this region acts to trap particulate matter and block the dispersion of pollutants. Recently, Lu et al. (2015) used the Community Multiscale Air Quality Model (CMAQ) to simulate the wet deposition of acid substances (sulfate and nitrate) over this region and showed that the amount of the acid substances was much greater than that in developed countries.

Particulate matter has been shown to have substantial impact on human beings' health (Kim et al., 2015). Epidemiological studies have proven that exposure to PM_{10} or $PM_{2.5}$ can cause increases in hospital outpatient visits, hospital admissions, and mortality from respiratory causes, cardiovascular causes, and lung cancer (Samoli et al., 2008; Cao et al., 2011; Shang et al., 2013). Lim et al. (2012) pointed out that household air pollution has become one of the top three risk factors for global disease burden. Lelieveld et al. (2015) estimated that $PM_{2.5}$ together with O_3 caused around 3.3 million premature mortality around the world in 2010. Apte et al. (2015) also found that 750,000 premature mortality due to exposure to $PM_{2.5}$ can be avoided if the governments in the world follow the WHO interim guideline in 2010. Several studies have been published on the negative health effects of particulate matter in the PRD region. Jahn et al. (2011) found that 10,000 premature non-accidental deaths could be avoided in Guangzhou (the capital city of the PRD region) if the particulate matter concentration level met the annual national air quality standard. Xie et al. (2011) used data from the monitoring stations in this region to evaluate the health effects of PM_{10} and $PM_{2.5}$ and showed that 42,000 and 40,000 deaths, respectively, could be avoided if no PM_{10} and $PM_{2.5}$ pollution was present. Huang et al. (2012) also used station observation data to estimate the health burden caused by particulate matter in this region. Lu et al. (2016a) used the WRF-CMAQ system to study the short-term health and cost benefits of air pollution over this region and found that adverse health effects were correlated with urbanization from the model perspective. Each of these studies showed that particulate matter caused a heavy health and economic burden in this region.

Several factors influence the accuracy of estimations of health burden with both point observation data and chemical transport model simulation. Although the observation data can show time series differences, these data are restricted to several observation points over this region and cannot be used to reveal spatial variance. Although the simulation results with the air quality model can present the pollutant concentration spatially, the accuracy of the results is restricted by the static emission inventory (Zheng et al., 2009). Hence, the results cannot reveal the true emission modification, and the error would increase for long-term simulation (e.g., 10 years). Satellite data do not have the drawbacks mentioned above; they can show the pollutant concentration spatially and are not restricted by the static emission inventory issue. Therefore, the two factors that influence the accuracy of estimation mentioned above could be solved with the application of satellite-derived particulate matter data. In China, Zheng et al. (2015) applied $PM_{2.5}$ data derived from ground-observed Aerosol Optical Depth (AOD) to evaluate the human health impact in Beijing.

Because of the serious air pollution issue, the "Eleventh Five-Year" (2006–2010) and "Twelfth Five-Year" (2011–2015) emission reduction plans were carried out in this region (Zhong et al., 2013). Hence, it is of great significance to evaluate whether these emission control strategies can decrease the health burden caused by the particulate matter concentration over this region. In this study, we use satellite-derived PM_{10} data and $PM_{2.5}$ data combined with concentration response function (C-R function) to estimate the outpatient visits, hospital admissions, and mortality from 2004 to 2013 in the PRD region. We estimate the premature mortality from cerebrovascular disease (stroke), chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), and lung cancer (LC). The value of statistical life (VSL) method is also applied to evaluate the economic loss attributable to $PM_{2.5}$. In Section 2, a description of the satellite data, the C-R function, and the economic loss estimation methods are introduced. Health burden estimation, the urbanization effect, and uncertainty analysis are presented in Section 3. The overall study is summarized in Section 4.

2. Methods

2.1. Satellite-retrieved $PM_{2.5}$ data and PM_{10} data

Recent developments in satellite-based remote sensing provide a useful alternative for the estimation of PM concentrations at a large spatial scale (Brauer et al., 2012; van Donkelaar et al., 2010). Research in China, however, has been hindered by limited long-term historical PM concentration data (Ma et al., 2015; Peng et al., 2016). Two of our recent studies first estimated more than a decade of PM_{10} and $PM_{2.5}$ concentration data, respectively, in the PRD at a 1-km resolution (Li et al., 2015; Lin et al., 2016). The algorithms were constructed on the basis of the physical understanding between the satellite-observed AOD and the ground-level PM concentration. The 1-km AOD data at 0.55 μm in the PRD were retrieved by the dark-target land algorithm from spectral data from two MODIS (Moderate Resolution Imaging Spectroradiometer) instruments aboard Terra and Aqua and from our own look-up table, which was more compatible with the local conditions (Li et al., 2005a). A MODIS cloud mask with 99% cloud-free criteria is used to exclude cloudy pixels. Retrieval errors within 15%–20% of sunphotometer measurements, which has the same accuracy as MODIS standard aerosol products, were found in Beijing and Hong Kong (Li et al., 2005a, 2005b). The retrieved AOD over the PRD from 2001 to 2013 was also validated with observations from the Aerosol Robotic NETwork (AERONET) (Li et al., 2015).

Furthermore, the models were driven by observational data based on meteorological data (visibility and relative humidity data) obtained from the global telecommunications system (GTS) stations of the World Meteorological Organization. In general, the ground-level $PM_{2.5}$ retrieval process required vertical correction and humidity correction. The surface extinction coefficient can be derived with Eq. (1):

$$AOD = \sigma_{a,0} \cdot H \tag{1}$$

where $\sigma_{a,0}$ is the surface aerosol extinction coefficient and H is the aerosol scale height. The aerosol scale height can be deemed as the equivalent depth of optically active aerosol layer (Liu et al., 2005). The scale height at the GTS station can be estimated via satellite observed AOD and in situ visibility-derived aerosol extinction coefficient. The scale height in other places can then be acquired by using interpolation method assuming the scale height varies smoothly regionally. Since the aerosol size is influenced by the water content in the atmosphere, hence, humidity correction is needed to adjust the effect of water vapor (Lee et al., 2008). The humidity correction can be derived by Eq. (2):

$$f(RH) = \left(\frac{1-RH}{1-RH_0}\right)^{-\gamma} \tag{2}$$

where RH_0 is 40% (represents the dry condition) and γ is the Hänel growth coefficient, depending on the aerosol property (Kotchenrutheret al., 1999; Randriamiarisoa et al., 2006). Here, we assume that RH varies smoothly and that the RH between the GTS stations was acquired by spatial interpolation. Finally, the surface $PM_{2.5}$ concentration is connected to AOD via Eq. (3):

$$PM_{2.5} = \frac{\frac{AOD}{H}}{K \cdot \left(\frac{1-RH}{1-RH_0}\right)^{-\gamma'}} \tag{3}$$

where K is the integrated reference value and γ' represents the integrated humidity effect. We used the same method to retrieve the PM_{10} data;