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Estimation of health and economic costs of air pollution over the Pearl River Delta region in China

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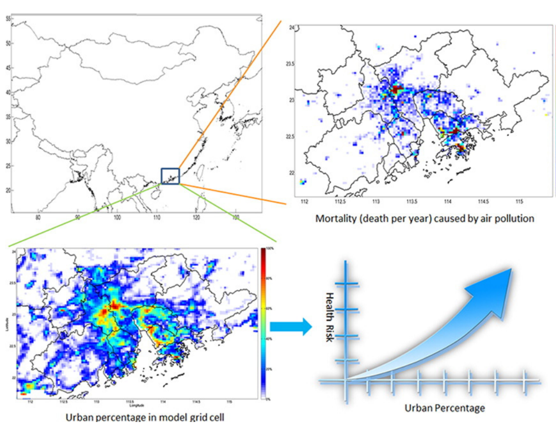
HIGHLIGHTS

- Mortality and morbidity due to ambient pollutants in PRD region were estimated.
- Health risk exerted by ambient pollutants increased with the urbanization process.
- The estimated health cost was around 1.4% to 2.3% of local GDP in 2013.
- More traffic control policies are needed to guarantee the citizens' health benefit.

GRAPHICAL ABSTRACT



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ABSTRACT

The Pearl River Delta region (PRD) is the economic growth engine of China and also one of the most urbanized regions in the world. As a two-sided sword, rapid economic development causes air pollution and poses adverse health effects to the citizens in this area. This work estimated the negative health effects in the PRD caused by the four major ambient pollutants (SO_2, NO_2, O_3 and PM_{10}) from 2010 to 2013 by using a log linear exposure–response function and the WRF-CMAQ modeling system. Economic loss due to mortality and morbidity was evaluated by the value of statistical life (VSL) and cost of illness (COI) methods. The results show that the overall possible short-term all-cause mortality due to NO_2, O_3 and PM_{10} reached the highest in 2013 with the values being 13,217–22,800. The highest total economic loss, which ranged from 14,768 to 25,305 million USD, occurred in 2013 and was equivalent to 1.4%–2.3% of the local gross domestic product. The monthly profile of cases of negative health effects varied by city and the types of ambient pollutants. The ratio of mortality attributed to air pollutants to total population was higher in urban areas than in rural areas. People living in the countryside should consider the possible adverse health effects of urban areas before they plan a move to the city. The results show that the health burden caused by the ambient pollutants over this region is serious and suggest that tighter control policies should be implemented in the future to reduce the level of air pollution.

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1. Introduction

With the implementation of the Reform and Open Policy in the late 1970s, the Pearl River Delta region (PRD) has been transformed from an agricultural and fisheries economy to one of the major manufacturing hubs of the world. As one of the pioneering areas of reform in China, the PRD has also been called the "World's Factory" due to substantial investments made by foreign sources from around the world. Ever since the launch of the reform policy in 1979, the annual growth in the gross domestic product (GDP) over the last three decades has reached as much as 13.5% annually. Sustained and rapid economic growth has brought enormous wealth to the local residents, but with the simultaneous worsening of air quality, environmental and ecological conditions have deteriorated. This high-speed development is being achieved by building more and more energy-intensive industries and factories, and as a result, much larger amounts of coal are being consumed than in the past. At the same time, vehicle ownership is growing and increasing the amounts of NO_x emitted into the atmosphere. Over the most recent 10 years, the PRD has been suffering from numerous air pollution issues, including episodes of high ozone (O_3), acid deposition and regional haze events, among others.

Given the continued deterioration of the ambient environment in this region, much observational-and numerical model-based research focusing on this area has been carried out in the most recent 10 years. For example, Kwok et al. (2010) used the Community Multi-scale Air Quality (CMAQ) model to simulate the gaseous and particulate pollutants in this region and performed a detailed analysis of spatial distribution and seasonal variation of ambient pollutants over this area. Wang et al. (2014) conducted a long-term trends study of $PM_{2.5}$ from 2000 to 2010 and found that the National Air Quality standards were not met in any of these 11 years.

To quantify how ambient pollutants affect human beings, estimations of health burden that can provide information on mortality and economic loss due to air pollution in specific regions are highly needed. Many studies of this topic have been carried out in other regions around the world. For example, Fann et al. (2012a,2012b) and Fann and Risley (2013) applied model and observation data combining with BenMAP to analyze the mortality due to the exposure to O_3 and $PM_{2.5}$ in the US; Lelieveld et al. (2013) used a global model to evaluate premature mortality due to $PM_{2.5}$ and O_3; and Wang et al. (2015) applied WRF–CMAQ system to evaluate mortality and economic loss due to $PM_{2.5}$ in the Yangtze River Delta region. In PRD, Huang et al. (2012) applied observational data to calculate the health burden caused by particulate matter in this region, and Ding et al. (2015) applied CMAQ–BenMAP to study the $PM_{2.5}$ health burden in Guangzhou during the Asian Games. Besides particulate matter, the levels of O_3, sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) are also of concern over the PRD.

Previous studies only focused on the adverse health effects from a single pollutant, and thus we cannot grasp or compare the magnitude of mortality and morbidity caused by different pollutants. In this study, we applied the WRF–CMAQ modeling system to estimate and compare short-term mortality and economic loss due to four major ambient pollutants (PM_{10}, SO_2, NO_2 and O_3) over the PRD during 2010 to 2013. The 'short-term mortality' means the mortality from short-term exposure in this article. This study can help us to answer four questions: 1) What is the magnitude of the estimated health burden (hospital admissions, outpatient visits and mortality and economic loss) due to the major air pollutants in the PRD?; 2) How has the health burden varied over the four study years under different yearly meteorological conditions?; 3) What are the monthly variations in mortality and morbidity due to the different pollutants?; and 4) What effects of urbanization on the health burden can be attributed to ambient pollutants?

2. Methods

2.1. Modeling system

The WRF–SMOKE (Sparse Matrix Operator Kernel Emissions)–CMAQ air quality system was used to simulate the air quality conditions from 2010 through 2013 over the PRD area. We applied a one-way nested method for the simulation, and the grid resolutions were 27 km, 9 km and 3 k m. Details of the domain extent can be found in Fig. 1. We applied domain 3 (3 km) to study the health burden. The WRF configuration can be found in Yao et al. (2014). For the CMAQ setting, cloud_acm_ae5, aero5 and cb05 were chosen as the cloud module, aerosol module and gas phase mechanism, respectively, in the simulation. To better catch the Asian background concentrations of the pollutants, pre-generated GEOS-Chem outputs were used for initial and boundary conditions for domain 1 (27 km). The INTEX-B Asian emission inventory (Zhang et al., 2009) was used for domain 1 and domain 2 (9 km), whereas a highly resolved PRD regional emission inventory was prepared for domain 3 (Zheng et al., 2009). MEGAN (Model of Emissions of Gases and Aerosols from Nature) was used to generate the biogenic volatile organic compound emission for all three domains. The CMAQ model performance matrix for daily pollutants in the PRD is shown in Table S1. In general, our results were comparable to those of other similar studies of this region (Kwok et al., 2010; Wu et al., 2012 and Li et al., 2012).

2.2. C-R functions

We calculated the air pollution associated with outpatient visits, hospital admissions and short-term premature mortality by applying log-linear C-R functions (Eq. 1). This function can be used only to estimate negative health effect (e.g., respiratory mortality and cardiovascular mortality) from diseases for which epidemiological studies already exist.

$$\Delta y = y_0\left(e^{\beta\Delta x} - 1\right)Pop \tag{1}$$

where Δy represents premature mortality or hospital admission caused by the related ambient pollutant. y_o is the baseline incidence rate for specific diseases per unit population. Exponential factor β is the exposure–response coefficient calculated via $\beta = \ln(RR)/\Delta x$ and $ER(\%) = (RR\text{-}1)^{*}100\%$. Relative risk (RR) and Excess risk (ER) for related health endpoint can be found in the epidemiological studies. Δx in Eq. 1 represents the difference between the true exposure concentration and the threshold concentration below which no adverse health effect occurs for the ambient pollutant. However, it is still controversial to define the safe threshold for ambient pollutants. Hence, in this study, we applied the natural background concentration for the lower limit of related ambient pollutants (Fiore et al., 2002; World Health Organization, 2000; Veira et al., 2013), as listed in Table S3. Pop is the spatial distribution of the population over the PRD in domain 3.

The rates of hospital outpatient visits, hospital admissions and mortality were acquired from the China Statistical Yearbook (National Bureau of Statistics of China, 2011–2014). The health endpoints we evaluated included cardiovascular mortality, respiratory mortality, all-cause outpatient visits and all-cause hospital admissions, as shown in Table S4. The three annual mortality rates (first three rows) are for the whole of China, and the annual rates of outpatient visits and hospital admissions (fourth and fifth rows) are for Guangdong Province. This table shows that the rates of hospital outpatient visits and hospital admissions increased gradually from 2010 to 2013 in Guangdong.

The exposure–response coefficient derived from excess risk is the core for quantitative evaluation of health effects caused by air pollutants. Here, we applied the coefficient reported in local epidemiological studies. Because few O_3-related epidemiological studies for morbidity have been done in China, we did not evaluate hospital admissions and