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Assessment of short-term $PM_{2.5}$-related mortality due to different emission sources in the Yangtze River Delta, China

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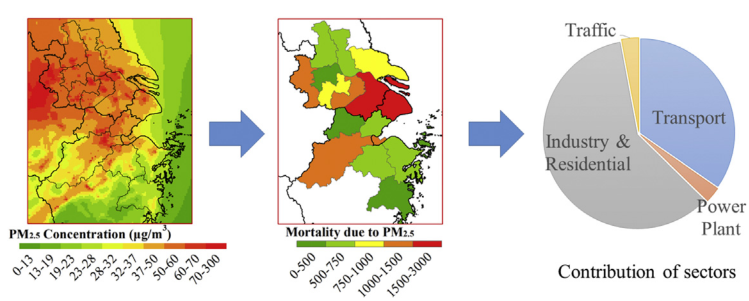
HIGHLIGHTS

- Short-term mortality due to $PM_{2.5}$ in YRD is estimated to be 13,162 in 2010.
- The economic loss due to $PM_{2.5}$ is 22.1 billion Chinese Yuan.
- The industry and residential sectors account for over 50% of the damages.
- The contribution of different air pollutant emissions varies with seasons.

GRAPHICAL ABSTRACT



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ABSTRACT

Air pollution is a major environmental risk to health. In this study, short-term premature mortality due to particulate matter equal to or less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) in the Yangtze River Delta (YRD) is estimated by using a PC-based human health benefits software. The economic loss is assessed by using the willingness to pay (WTP) method. The contributions of each region, sector and gaseous precursor are also determined by employing brute-force method. The results show that, in the YRD in 2010, the short-term premature deaths caused by $PM_{2.5}$ are estimated to be 13,162 (95% confidence interval (CI): 10,761-15,554), while the economic loss is 22.1 (95% CI: 18.1–26.1) billion Chinese Yuan. The industrial and residential sectors contributed the most, accounting for more than 50% of the total economic loss. Emissions of primary $PM_{2.5}$ and NH_3 are major contributors to the health-related loss in winter, while the contribution of gaseous precursors such as SO_2 and NO_x is higher than primary $PM_{2.5}$ in summer.

1. Introduction

Located in the eastern part of China, the Yangtze River Delta (YRD) is the largest estuary delta in China. It covers the municipality of Shanghai, southern Jiangsu Province, and eastern and northern Zhejiang Province. As one of the most densely populated

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regions of China, the YRD contains 107 million people with an area of 213 thousands square kilometers. Accompanied with a rapid economic development and a dramatic industrial expansion in the past two decades, the YRD has experienced a sharp increase in energy consumption and air pollutants emissions, which leads to serious air pollution problem. In 2010, the average emission intensity in the YRD for SO_2, NO_X, particulate matter equal to or less than 10 μm in aerodynamic diameter (PM_{10}), particulate matter equal to or less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$), non-methane volatile organic compounds (NMVOCs) and NH_3 were 2–7 times higher than the national average (Fu et al., 2013). In 2013, the annual average concentrations of $PM_{2.5}$ in Shanghai, Nanjing and Hangzhou were 56 μg/m^3, 75 μg/m^3 and 64 μg/m^3, respectively (Wang et al., 2014c), which were 5–7 times of the World Health Organization Air Quality Guidelines (WHO, 2005) and far above the current annual air quality standards of 35 μg/m^3 (GB 3095-2012). A significant decrease in visibility was evident judging from historical record (Chang et al., 2009; Cheng et al., 2013a; Gao et al., 2011). Since 2010, the YRD has been identified as a key area for joint prevention and control of air pollution, which is an important air pollution control plan for China (Wang and Hao, 2012). The PM pollution is a key air pollution problem in the YRD, leading to adverse health impacts.

Several studies have evaluated the health loss due to PM on national or regional scale in China. The Global Burden of Disease 2010 used integrated exposure-response model and estimated that the number of deaths attributable to ambient $PM_{2.5}$ was 3.2 million worldwide and 1.2 million in China in 2010 (Burnett et al., 2014; Lim et al., 2012). Monitoring data are limited before the China National Urban Air Quality Real-time Publishing Platform was introduced publically in January, 2013 (Jiang et al., 2014). Most studies used PM_{10} and total suspended particles (TSPs) to estimate health impact on exposure to PM, or estimated effect of $PM_{2.5}$ with the derivative coefficient from the epidemiological reference linking the mortality and PM_{10}. On national scale, Cheng et al. (2013b) estimated the PM_{10}-related premature deaths increased from 418,000 to 514,000 from 2001 to 2011. The World Bank (2007) estimated the health cost of urban PM pollution in China in 2003 to be 157 billion Chinese Yuan by using adjusted human capital (AHC) method and 520 billion Chinese Yuan by using the value of statistical life (VSL) method. In addition to these national air pollution studies, the total health loss due to PM pollution on a region or city scale has also been estimated (Huang et al., 2012a; Tang et al., 2014; Zhang et al., 2007).

Epidemiologic studies in the United States and worldwide have demonstrated more robust associations with fine particular matters. Pope and Dockery (2006) reviewed the progress in the evaluation of PM health effects. In the United States (US), $PM_{2.5}$ air pollution and mortality were linked in the often cited Six Cities Study, where an association was reported with lung cancer- and cardiopulmonary disease-related mortality (Dockery et al., 1993). Pope et al. (1995) reported an association between $PM_{2.5}$ and all cause, cardiopulmonary, and lung cancer mortality. In China, substantial progress has been made on epidemiological studies since 2005. Several short-term studies were done in recent years (Cao et al., 2012; Guo et al., 2009; Huang et al., 2012b; Kan et al., 2007; Shang et al., 2013; Venners et al., 2003; Yang et al., 2012), including the systematic multi-cities research, “China Air Pollution and Health Effects Study” (CAPES) (Chen et al., 2011). Impacts of long-term exposure to $PM_{2.5}$ are limited in China. Together with the limit of observational data, there are still only a few studies assessing the premature mortality caused by $PM_{2.5}$ with Chinese local concentration-response (C-R) coefficient.

Emission reductions in different sectors may have different levels of effectiveness on reducing human exposure (Li et al., 2004; Streets et al., 1999). Besides, the purpose of establishment and revision of ambient air quality standards is to protect public health and welfare. Therefore, evaluation of health impact and the economic loss due to emissions of various pollutants and different sectors could potentially help for future pollution control. Fann et al. (2009, 2012) assessed the human health impacts and monetized benefits due to different emission sectors by applying the Response Surface Model (RSM) and CAMx. In China, Zhou et al. (2010, 2014) discussed the contribution of and NOx emissions of different sectors under different emission control scenarios. However, the researches on contribution of different gaseous precursors and total contribution of one sector are still lacked.

In this study, Environmental Benefits Mapping and Analysis Program Community Edition (BenMAP CE) with China's local epidemiological studies and health data is employed to estimate the premature mortality caused by $PM_{2.5}$ in the YRD region in 2010. The spatial and temporal distribution of $PM_{2.5}$ concentrations are simulated by Community Multi-scale Air Quality (CMAQ) modeling system. Source apportionment was conducted on the causes of $PM_{2.5}$–related premature mortality. The contributions of different regions were evaluated and the contribution of different sectors and gaseous precursors were also assessed. The results will help prioritize future pollution control strategies among the different regions, sectors and gaseous precursors in the YRD.

2. Materials and methods

2.1. $PM_{2.5}$ modeling system and emission inventory

To get the $PM_{2.5}$ concentration for health assessment, Weather Research & Forecasting Model (WRF) - CMAQ modeling system is utilized in this study. WRF version 3.3 is applied to generate the meteorological fields for CMAQ. The spatial distributions and temporal variations of $PM_{2.5}$ are simulated by the CMAQ of version 4.7.1. Triple nesting simulation domains are employed in this study, as shown in Fig. 1. Domain 1 covers most of China with 36 km*36 km resolution, Domain 2 covers eastern China with 12 km*12 km resolution, and Domain 3 covers the YRD region with 4 km*4 km resolution, respectively. The vertical resolution includes 14 layers from the surface to the tropopause, consistent with our previous work (Wang et al., 2010b). A combination of a few emission inventories developed by Tsinghua University is used as the input of the modeling system. The anthropogenic emissions inventory for Domain 1 and Domain 2 is from Wang et al. (2014b), Zhao et al. (2013a, 2013c). A high-resolution anthropogenic emission inventory for the YRD region from Fu et al. (2013) is used in Domain 3. The CMAQ model, which is developed by U.S. Environmental Protection Agency (EPA), has been tested, evaluated, and applied in China (Wang et al., 2010b; Zhao et al., 2011, 2013a). The simulation periods are selected as January, May, August and November, representing the average concentration in each season. The annual average $PM_{2.5}$ is represented by the average concentration of these four months. The configurations of chemical initial conditions and boundary conditions are consistent with our previous papers (Wang et al., 2014a; Zhao et al., 2014) and summarized in SI. The simulated meteorological parameters and PM concentrations have been evaluated by comparison with observational data, which indicated that the model can well capture the temporal trend and spatial distribution. The detailed methods and results of validation were reported in our previous work (Zhao et al., 2014) and shown in Supplemental Information (SI, Table S1 to S4 and Figure S1).