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# Characterization of haze episodes and factors contributing to their formation using a panel model

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## HIGHLIGHTS

- Dynamic panel model was applied to the $PM_{2.5}$ study.
- Strong lag effect and neighbor effect were found of the daily $PM_{2.5}$ pollution.
- Natural and anthropogenic factors dominated the daily and annual $PM_{2.5}$, respectively.
- The simple dynamic panel model can well predict annual $PM_{2.5}$ changes on city scale.

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## ABSTRACT

A haze episode is a complex pollution process with high levels of fine particulate matter smaller than 2.5 μm ($PM_{2.5}$). Understanding factors contributing to their formation is crucial to mitigate $PM_{2.5}$ pollution, which varies substantially on the daily and city scales. In this study, we attempted to introduce the dynamic panel model that uses the group deviation method to generate unbiased estimates of contributions from different factors by eliminating time-invariant confounding variables. Taking 25 cities in the Yangtze Delta Region (YDR), China, as a case study and we analyzed how natural factors (e.g., wind) and anthropogenic emissions (e.g., sulfur dioxide ($SO_2$)) together contribute to $PM_{2.5}$ pollution. Results showed that there was significant lag effect on $PM_{2.5}$ concentration, and approximately 45% of the $PM_{2.5}$ remained from one day to the next. On the contrary, present day's emission had little effect on its $PM_{2.5}$ concentration. It suggested that daily variation of $PM_{2.5}$ concentration was largely affected by natural factors, while the long term $PM_{2.5}$ pollution such as annual concentration was more determined by anthropogenic emissions. The unbiased estimates of this simple dynamic panel model could well predict the annual changes of $PM_{2.5}$ concentration with an uncertainty of less than 2% on city scale. Reducing $SO_2$ and nitrogen oxide ($NO_x$) emissions could mitigate $PM_{2.5}$ pollution to some extent in the YDR; however, to achieve the clean air standard, more pollutants such as ammonia should be added to the emission reduction list. The analyses provide an alternative method to easily quantify contributing factors and their variability to air pollution. It could be helpful to better understand the confounding factors on the assessment of air pollution governance despite the panel model still need to be improved on aspects such as long-range transportation.



## 1. Introduction

Haze episodes have a substantial health impact (Matus et al., 2012; Guo et al., 2014). Compared to other air pollutants, such as $PM_{10}$ (fine particulate matter smaller than 10 μm), $SO_2$ and $NO_x$, $PM_{2.5}$ can enter and accumulate in the alveolus, leading to long-term chronic diseases (Li and Zhang, 2014). Therefore, the World Health Organization (WHO) recommends an annual-average $PM_{2.5}$ air quality guideline of 10 μg $m^{-3}$ from the perspective of public health. In many cities, especially in developing countries, the WHO standard cannot be met and is even exceeded by two orders of

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magnitude (de Sherbinin et al., 2014; MEPC, 2014). $PM_{2.5}$ pollution has become one of the major causes for human life year loss, costing in billions of dollars in human health damage (Sutton et al., 2011; Matus et al., 2012). $PM_{2.5}$ has been on the policy agenda in the United States and Europe for a long time and recent activities such as the revision of the Gothenburg Protocol have firmly established $PM_{2.5}$ in environmental policy (Sutton et al., 2011; Vieno et al., 2014; Kiesewetter et al., 2015). To mitigate air pollution, policy-makers start to concern $PM_{2.5}$ in more and more countries such as China began to regularly monitor and report daily $PM_{2.5}$ concentrations for major cities in 2013 (MEPC, 2014).

$PM_{2.5}$ concentrations can have episodic variations related to both natural and anthropogenic factors (Guo et al., 2014). Pollutant emissions from human activities contribute to $PM_{2.5}$ formation (Huang et al., 2014; Vieno et al., 2015; Kiesewetter et al., 2015). After emission, photochemical reactions among multiple pollutants usually occur and produce secondary $PM_{2.5}$, which accounts for the majority of severe hazes in many cities and world regions (Jimenez et al., 2009; Zhang et al., 2009). To understand the sources of air pollution, many studies have focused on the analyses of chemical compositions of $PM_{2.5}$, based on which receptor models such as chemical mass balance (CMB) is used to identify the emission sources (Huang et al., 2014). To capture the contribution from natural factors, atmospheric chemistry transport models (e.g. EMEP, CMAQ) are developed to include natural emissions and their contribution to $PM_{2.5}$ formation, as well as taking into account full chemical processes and meteorological and climatological factors (Vieno et al., 2014). There are many non-ignorable sources of variability in the distribution and transmission patterns of $PM_{2.5}$, confounded by meteorological conditions, emissions at source and secondary chemical generation (Liang et al., 2015). The relationship between $PM_{2.5}$ and the confounding factors remains unclear due to large variability in the observed $PM_{2.5}$ data (Liang et al., 2015).

$PM_{2.5}$ concentrations vary significantly on a daily scale (Hu et al., 2014; Vieno et al., 2015). To explain these variations, statistical inference based on monitoring data have tested the relationships between $PM_{2.5}$ and meteorological factors via multiple methods, such as a principal component analysis and multiple linear regression (Li et al., 2014; Tian et al., 2014). However, due to lacking daily pollutant emission data, these analyses are thought to be biased from the multiple interactions among $PM_{2.5}$ pollution, meteorological factors and pollutant emissions (Guo et al., 2014; Vieno et al., 2015). Meanwhile, these statistical inferences used raw monitoring data to analyze the relationships, and they cannot eliminate the effects from time-invariant confounding variables such as specific location of a monitoring station. Although atmospheric chemistry transport models can help to address these issues mentioned above, they still do not fully account for the uncertainties derived from confounding variables (Vieno et al., 2014; Kiesewetter et al., 2015). Furthermore, the atmospheric chemistry transport models are usually based on gridded data and they are powerful to explain the regional variations of $PM_{2.5}$ concentrations, nevertheless, uncertainties existed when downscaling to fit the monitoring data in cities. Thus, a comprehensive analysis of the daily city scale $PM_{2.5}$ concentration by using monitoring data is imperative and important to better understand how $PM_{2.5}$ pollution varies.

China has recently experienced serious haze. In 2014, the annual average $PM_{2.5}$ concentrations in 190 major cities in China exceeded the clean air standard as recommended by the WHO, with the highest one larger than 130 μg $m^{-3}$ (MEPC, 2014). Serious haze in Northern China has caused a loss of up to 5 life years on average, significantly damaging human health (Chen et al., 2013). To mitigate the $PM_{2.5}$ pollution in China, the central government launched the "Clean Air Act" (CAA) in 2013 and identified emission reduction targets of $SO_2$ and $NO_x$ for each city (MEPC, 2014). Meanwhile, each city has its own goal regarding the $PM_{2.5}$ concentration in 2017 based on the CAA, which is generally 10–25% lower than its 2012 level. To achieve the mitigation goals, the amount of pollutant emissions that should be reduced is crucial to all cities. This amount determines their future development pathway—to what degree they should change their energy or industrial structure to reduce the pollutant emission with economic growth. Due to multiple interactions among $PM_{2.5}$ pollution, pollutant emissions and meteorological factors, translating the $PM_{2.5}$ mitigation goal into reductions of pollutant emissions must consider regional transportation. In this study, we chose the Yangtze Delta Region (YDR), the most developed region suffering severe air pollution in China, as a case study (Fig. 1). Meteorological factors, such as daily average wind speeds and temperature, and anthropogenic factors, such as pollutant emissions, vary substantially across cities in the YDR. Thus, this region is well suited as a typical case to conduct an attribution analysis on haze episodes. Here, we first compile daily pollutant emission data ($SO_2$ and $NO_x$) to match daily $PM_{2.5}$ and meteorological data. Then, a dynamic panel data (DPD) model (Wooldridge, 2010) was introduced to analyze the multiple relationships among these three datasets based on to what degree pollutants should be reduced to achieve the CAA goal in each city in the YDR.

## 2. Methods

### 2.1. Study area

The YDR is located in the eastern coastal area of China (116°23′–122°59′E; 27°11′–34°54′N), including two provinces (Zhejiang and Jiangsu) and one municipality (Shanghai), totaling 25 cities (Fig. 1). The YDR covers an area of 210,700 $km^2$ with a population of 156 million, one of the most populous regions worldwide. The YDR has a subtropical monsoon climate with large variations in seasonal temperature (0–32 °C, average 16 °C) and precipitation (<1–4 mm $day^{-1}$, 1200 mm $yr^{-1}$). In both the

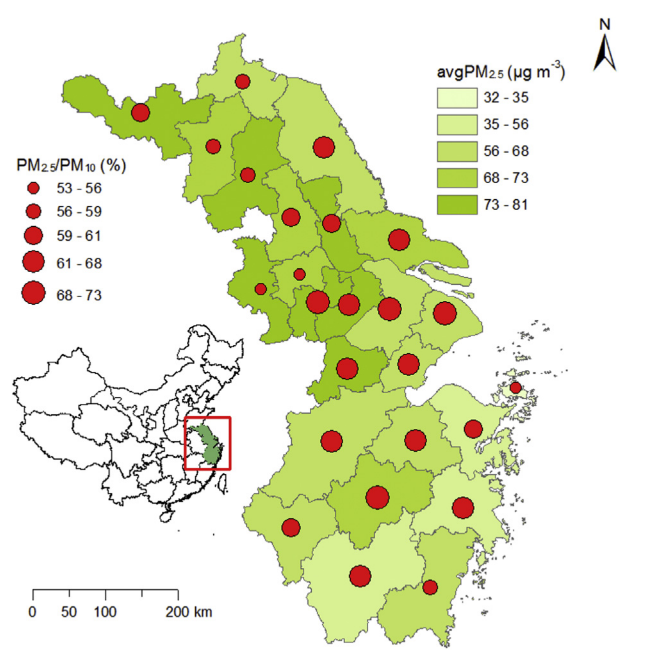


**Fig. 1.** Location of the Yangtze Delta Region (YDR) and the annual average $PM_{2.5}$ and $PM_{10}$ pollution in all the cities of the YDR in 2013.