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Examining the effects of socioeconomic development on fine particulate matter ($PM_{2.5}$) in China's cities using spatial regression and the geographical detector technique

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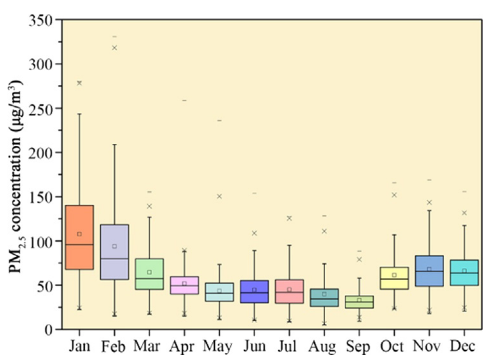
HIGHLIGHTS

- The direction and strength of the link between $PM_{2.5}$ level and their drivers are analyzed.
- Spatial regression and geographical detector techniques are used.
- A spatial agglomeration effect was identified in city-level $PM_{2.5}$ level.
- Population density, industrial structure, industrial dust, and road density increase $PM_{2.5}$ level.
- Trade openness and electricity consumption have no significant effect on $PM_{2.5}$ level.

GRAPHICAL ABSTRACT



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ABSTRACT

The frequent occurrence of extreme smog episodes in recent years has begun to present a serious threat to human health. In addition to pollutant emissions and meteorological conditions, fine particulate matter ($PM_{2.5}$) is also influenced by socioeconomic development. Thus, identifying the potential effects of socioeconomic development on $PM_{2.5}$ variations can provide insights into particulate pollution control. This study applied spatial regression and the geographical detector technique for assessing the directions and strength of association between socioeconomic factors and $PM_{2.5}$ concentrations, using data collected from 945 monitoring stations in 190 Chinese cities in 2014. The results indicated that the annual average $PM_{2.5}$ concentrations is 61 ± 20 μg/m^3, and cites with more than 75 μg/m^3 were mainly located in North China, especially in Tianjin and Hebei province. We also identified a marked seasonal variation in concentrations levels, with the highest level in winter due to coal consumption, lower temperatures, and less rainfall than in summer. Monthly variations followed a "U-shaped" pattern, with a down trend from January and an inflection point in September and then an increasing trend from October. The results of spatial regression indicated that population density, industrial structure, industrial soot (dust) emissions, and road density have a significantly positive effect on $PM_{2.5}$ concentrations, with a significantly negative influence exerted only by economic growth. In addition, trade openness and electricity consumption were found to have no significant impact on $PM_{2.5}$ concentrations. Using the geographical detector technique, the strength of association between the five significant drivers and $PM_{2.5}$ concentrations was further analyzed. We found notable differences among the variables, with industrial soot (dust) emissions playing a greater role in the $PM_{2.5}$ concentrations than the other variables. These results will be helpful in

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understanding the dynamics and the underlying mechanisms at work in $PM_{2.5}$ concentrations in China at the city level, and thereby assisting the Chinese government in employing effective strategies to tackle pollution.

1. Introduction

Air pollution, especially in the form of fine particulate matter ($PM_{2.5}$), has become a serious issue not only for developed countries but also for the developing world (Cheng et al., 2016; Peng et al., 2016). China, the world's largest developing country, has suffered frequent extreme smog episodes in recent years. In addition, international headlines from 2013 onwards report that haze weather has become a common phenomenon in China (Guan et al., 2014; Rohde and Muller, 2015; Zhang et al., 2015; S.J. Wang et al., 2017a; Yang et al., 2017; Zhou et al., 2017). The urbanization rate in China increased from 17.9% in 1978 to 54.8% in 2015 and continues to grow (Wang et al., 2014, 2015, 2016a, b; Li et al., 2017; Liu et al., 2017). The country's continued urbanization means that more people will live in urban areas, resulting in greater pollutant emissions (NBSC, 2015). The core problems linked to the intense concentrations of $PM_{2.5}$ include increasing death rates due to cancer, reduced atmospheric visibility, and changes to ecosystems and to the global climate (Brauer et al., 2012; Kan et al., 2012; Madrigano et al., 2013). Due to its negative impacts on human health, a growing body of literature has explored the potential drivers of $PM_{2.5}$ concentrations, finding that meteorological conditions play an important role in $PM_{2.5}$ variations. However, in addition to such conditions, $PM_{2.5}$ concentrations are also influenced by human activities. Therefore, understanding the characteristics and potential socioeconomic drivers of $PM_{2.5}$ concentrations will be of benefit in the task of improving air quality.

The determinants of $PM_{2.5}$ concentrations are garnering much attention from scholars globally. A growing number of studies have dedicated enormous efforts to analyzing the causes of $PM_{2.5}$. These studies have found that natural conditions such as temperature, humidity, slope, ozone concentrations, and wind velocity have varying effects on $PM_{2.5}$ concentrations. For example, Pateraki et al. (2012) undertook research on the generation of fine particles, finding that humidity fluctuations and temperature values ranging from 1.9 °C to 21.7 °C maintain a strong correlation with urban $PM_{2.5}$ concentrations. He and Lin (2017) employed the generalized additive model (GAM) to examine the influencing factors of $PM_{2.5}$ concentrations variation in the Chinese city of Nanjing. $PM_{2.5}$ concentrations variation was found to be strongly associated with temperature, pressure, and water vapor pressure. Although a linear relationship was identified between wind and $PM_{2.5}$ concentrations variation, increased wind speeds were not found to cause changes in $PM_{2.5}$ concentrations levels. Some scholars have conversely argued that wind speeds above 2 m/s can decrease $PM_{2.5}$ exposures (Onat and Stakeeva, 2013). In addition to natural conditions, recent socioeconomic impact assessments have established an association between the concentrations of $PM_{2.5}$ and socioeconomic determinants including urban population, urban secondary industry fraction, per capita GDP, and energy consumption (Paatero et al., 2003; Wang and Fang, 2016; Lou et al., 2016). For instance, through their analysis of the concentrations of $PM_{2.5}$ from 2001 to 2010 in China, Lin et al. (2014) found that population, local economic growth, and urban area are the main driving factors influencing $PM_{2.5}$ concentrations. Han et al. (2014) used satellite data to examine the impact of urbanization on urban $PM_{2.5}$ concentrations. Their results suggested that urban population and the urban secondary industry fraction have a strong correlation with urban $PM_{2.5}$ concentrations. Hao and Liu (2016) used spatial regression to explore the relationship between $PM_{2.5}$ concentrations and urban development in China, showing that vehicles and industry strongly influenced $PM_{2.5}$ concentrations levels. Hua et al. (2015) suggested that industrial activities and vehicles were the main contributors to $PM_{2.5}$ in the Yangtze River Delta (YRD). Most previous large-scale estimations of $PM_{2.5}$ levels have depended on satellite data and satellite aerosol optical depth (AOD) combing with meteorological parameters (J. Wang et al., 2010; Kloog et al., 2012). For example, using remote sensing technique, scholars found that the annual $PM_{2.5}$ concentrations of most cities were much higher than 10 μg/m^3, the air quality guideline offered by the World Health Organization (WHO) (Han et al., 2014; Van et al., 2015). In addition, Cheng et al. (2016) found that Delhi, Cairo, Xi'an, Tianjin and Chengdu were the five most polluted megacities, with annual average $PM_{2.5}$ concentrations higher than 89 μg/m^3. The same study found that east-central China and the Indo-Gangetic Plain constitute highly-polluted nesting zones. However, the lack of sustained accuracy in such satellite data, which uses remotely-sensed AOD as a proxy for $PM_{2.5}$ concentrations, frequently misses values because of cloudy or hazy conditions, making it difficult to estimate the temporal characteristics and spatial distributions of near-ground $PM_{2.5}$. For this reason, it has been difficult to identify the characteristics of $PM_{2.5}$ concentrations in different time scales for a given region (Liu et al., 2005; Gupta et al., 2006; Paciorek and Liu, 2009; Hoff and Christopher, 2009). Compared to satellite data, monitoring data collected from China's National Environmental Monitoring Centre (CNEC) shows 24 h $PM_{2.5}$ concentrations for 190 cities utilizing 945 monitoring stations. Such data, which has been collected since 2014 in China, has the potential to reflect the spatial and temporal (annual average, seasonal, and monthly) characteristics of $PM_{2.5}$ level at both the national scale and for a target region.

Nowadays, a variety of models are available that can be used to identify the socioeconomic determinants of $PM_{2.5}$, including econometric analysis (S.J. Wang et al., 2017b), input-output models (Guan et al., 2014; Fang et al., 2013), the classical ordinary least square model, spatial regression (Hao and Liu, 2016), Geographically Weighted Regression (GWR) (Hu et al., 2013), and land-use regression (Mao et al., 2012). The merit of spatial model is that it can depict the $PM_{2.5}$ concentrations of different cities of spillover effects. So here employ the spatial to explore the direction of the $PM_{2.5}$ concentrations determinants. Besides, mechanism studies have not yet been conducted using the geographical detector technique for air pollutants. This technique is widely applied in evaluating the influence of factors which do not need a linear hypothesis to reveal the driving factors behind spatial stratified heterogeneity (J.F. Wang et al., 2010; Y. Wang et al., 2017). Given this, this present study used geographical detector technique in order to avoid factors that should be removed due to collinearity in the models, and to explore the spatial correlations between $PM_{2.5}$ concentrations (using monitoring data) and socioeconomic variables.

Mechanism research on $PM_{2.5}$ concentrations using monitoring data and the geographical detector technique is rare. Here, we employed data collected from continuous, year-long monitoring in 190 cities to describe the spatial and temporal (annual average, seasonal, and monthly) distribution of $PM_{2.5}$ concentrations. We also undertook a spatial regression and used the geographical detector technique to reveal the directions and strength of the impact of socioeconomic factors on $PM_{2.5}$ concentrations. The results of this analysis are beneficial for policy makers in formulating appropriate measures to enhance air quality.

2. Material and methodology

2.1. Conceptual framework

The main goal of this study was to highlight the influencing mechanisms of $PM_{2.5}$ levels from a socioeconomic perspective. As such, we