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Air pollution characteristics in China during 2015–2016: Spatiotemporal variations and key meteorological factors

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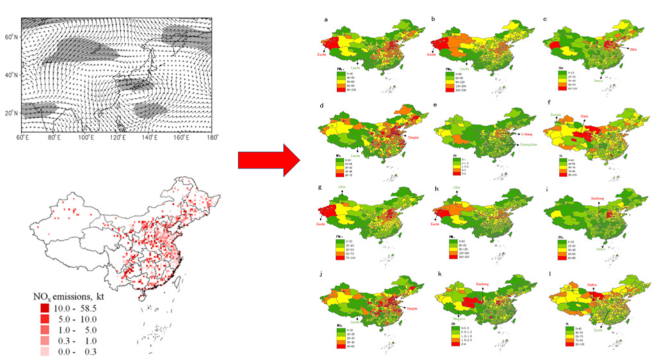
HIGHLIGHTS

- The concentrations of air pollutants except O_3 decreased significantly during 2015–2016.
- T and WS were major factors for all of these air pollutants in China.
- The effects of Prec and T on the PM displayed the higher values in Northeast China.

GRAPHICAL ABSTRACT



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ABSTRACT

With rapid economic development and urbanization, China has suffered from severe and persistent air pollution during the past years. In the work, the hourly data of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 in all of the prefecture-level cities (336 cities) during 2015–2016 were collected to uncover the spatiotemporal variations and influential factors of these pollutants in China. The average concentrations of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO decreased by 19.32%, 15.34%, 29.30%, 9.39%, and 8.00% from 2015 to 2016, suggesting the effects of efficient control measurements during this period. On the contrary, the O_3 concentration increased by 4.20% during the same period, which mainly owed to high volatile organic compounds (VOCs) loading. The concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO and NO_2 showed the highest and the lowest ones in winter and summer, respectively. However, the O_3 concentration peaked in summer, followed by ones in spring and autumn, and presented the lowest one in winter. All of the pollutants exhibited significantly weekly and diurnal cycle in China. $PM_{2.5}$, PM_{10}, SO_2, CO and NO_2 presented the higher concentrations on weekdays than those at weekends, all of which showed the bimodal pattern with two peaks at late night (21:00–22:00) and in morning (9:00–10:00), respectively. However, the O_3 concentration exhibited the highest value around 15:00. The statistical analysis suggested that the $PM_{2.5}$, PM_{10}, and SO_2 concentrations were significantly associated with precipitation (Prec), atmosphere temperature (T), and wind speed (WS). The CO and NO_2 concentrations displayed the significant relationship with T, while the O_3 concentration was closely linked to the sunshine duration (Tsun) and relative humidity (RH). T and WS

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were major factors affecting the accumulation of PM and gaseous pollutants at a national scale. At a spatial scale, Prec and T played the important roles on the PM distribution in Northeast China, and the effect of Prec on CO concentration decreased from Southeast China to Northwest China. The results shown herein provide a scientific insight into the meteorology impacts on air pollution over China.

1. Introduction

Along with the development of economy and urbanization, many regions including North China Plain (NCP), Yangtze River Delta (YRD), Pearl River Delta (PRD), and Sichuan Basin (SB) in China have witnessed increasingly severe air pollution in the past years. Dense industrial emission, heavy aerosol loading, and the adverse meteorological condition worsen air quality (Cheng et al., 2016; Wang et al., 2016c; Quan et al., 2014; Xu et al., 2016), degraded the horizontal visibility (Chang et al., 2009; Cao et al., 2015; Li et al., 2017a, 2017b; Chen et al., 2015; Zhao et al., 2018; Bi et al., 2014), and damaged the human health (Li et al., 2017a, 2017b; Ebenstein et al., 2017).

It was well documented that some particulate matter (PM) such as $PM_{2.5}$ and PM_{10}, and gaseous pollutants are main contributors to haze formation (Guo et al., 2014; Jihua et al., 2009). The coexistence of gaseous pollutants, including SO_2, NO_2, CO, and O_3 supplied a large number of reactants for fine particle formation and ageing, and thus influenced the chemical compositions, mixing states, and optical properties of aerosol particles, which could negatively affect air quality (Wang et al., 2014a). For instance, Cheng et al. (2016) confirmed that high loading of SO_2, NO_2, and $PM_{2.5}$ could enhance the sulfate formation at pH values of 5–6, consequently leading to haze formation. Apart from the effects on the air quality and climate change, both of PM and gaseous pollutants rendered remarkable damages to human health supported by many epidemiological studies. Kampa and Castanas (2008) proposed that $PM_{2.5}$ could penetrate the alveolar epithelium and initiated the respiratory and cardio-vascular diseases. Chauhan et al. (1998) and Rastogi et al. (1991) reported that nitrogen oxides generally increased the susceptibility to respiratory infection and the chronic exposure to ozone probably reduced the lung function. Following these work, Ebenstein et al. (2017) assessed the health effects of air pollutants at a national scale and confirmed that a 10-μg/m^3 increase of PM_{10} led to the reduction of life expectancy by 0.64 years in China based on the econometric model.

A growing body of researches focuses on the spatiotemporal variation of air pollutants in China (Wang et al., 2014b; Zhao et al., 2016; Tong et al., 2017). Xie et al. (2015) showed the spatiotemporal distribution of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 in all of the provincial capitals over China and found that the $PM_{2.5}$ and SO_2 displayed high concentrations in some cities of NCP. Li et al. (2014) observed that air pollution index (API) in Guangzhou remained consistently higher values compared with many cities of South China in the past decades. However, the analysis of pollutant concentrations in dozens of cities cannot accurately reflect the spatial variation of pollutants in China because of less monitoring sites. To overcome these defects, Li et al. (2017a, 2017b) selected 187 cities in China and employed many geo-statistic methods to elucidate the regional differentiation of the ambient pollutants. The spatial variation of $PM_{2.5}$ and PM_{10} could be also determined using the inversion of aerosol optical depth (AOD) (Bouet et al., 2016; You et al., 2015; Ma et al., 2016). However, the geo-statistic methods and satellite measurements only explained integrant spatial variability and presented many uncertainties (Just et al., 2015). Li et al. (2017a, 2017b) used three geo-statistic methods to investigate the spatiotemporal variation of air pollutants in China and found that these methods only explained 53–75% variances of air pollutants. Therefore, the result precisions using these methods were lower than those gained by the ground-based observations. To the best of our knowledge, no studies assessed the spatial distribution of the pollutants based on the data in all of the prefecture-level cities in China.

Apart from the contribution of high pollutant emission to fog-haze formation, unfavorable meteorological condition was generally treated as a dominant factor accounting for the generation of persistent haze episodes (Wang and Dai, 2016; Yu et al., 2018). The closed terrain in SB was not beneficial to the pollutant diffusion and high relative humidity (RH) in this region could promote haze formation (Yang et al., 2015). Furthermore, the aerosol particles were inclined to be transported from source areas to downwind regions, and the transport rate depended strongly upon wind speed (WS) (Zhang et al., 2015a, 2015b). Thus, it was necessary to decipher the relationship between the pollutant concentrations and the meteorological factors. Up to date, the relevance between multiple criteria pollutants and meteorological condition in dozens of cities have been reported previously (Lin et al., 2014; Tan et al., 2009), whereas the spatial relationships between the pollutants and meteorological factors at a national scale remained unknown. The correlation of the pollutants and the meteorological factors in several cities neglected the spatial heterogeneity of the pollutants, which existed widely at a large scale. Furthermore, the relevance between the pollutants and the meteorological factors was determined only using some traditional statistics (Li et al., 2014), which overlooked the spatial correlation of pollutants especially in the adjoining areas (He et al., 2017). Consequently, spatial statistical models should be applied to further explain the spatial autocorrelation of pollutants, especially at a national scale.

Here, the officially released data of the air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) in all of the 336 prefecture-level cities across China from January 2015 to December 2016 were collected to examine the air pollution status in China. The spatial correlations between air pollution and meteorological conditions were determined using correlation analysis, pathway analysis, spatial econometric model, and geographical weight regression (GWR). To the best of our knowledge, this is the first investigation of spatial relationships between air pollutants and meteorological factors at a national scale, which will deepen the understanding of haze formation in China.

2. Materials and methods

2.1. Air quality data description

In order to assess the status (i.e., spatiotemporal variation, key pollutants) of air pollution in China, the data of $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 during January 2015 and December 2016 were collected. The real-time monitoring data of these pollutants at all of the prefecture-level cities in China were obtained from National Environmental Monitoring Platform (https://www.aqistudy.cn/historydata/), which is open access to all of the people. The national environmental agency began to publish daily air pollution data of six pollutants at 74 major cities since January 2013 and expanded to all of the prefecture-level cities from January 2015, which covered the whole country and supplied a more detailed information about air pollution in China.

2.2. Meteorological factors and emission inventory

The meteorological data at all of the prefecture-level cities were obtained from the Chinese Meteorological Administration. The