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Spatiotemporal patterns and spatial clustering characteristics of air quality in China: A city level analysis

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ABSTRACT

This study utilized air quality data on six pollutants ($PM_{2.5}$, PM_{10}, O_3, CO, NO_2, and SO_2) obtained by monitoring for one year (from Jan 1 to Dec 31, 2016) in 338 Chinese cities at or above the prefectural level, and introduced the comprehensive air quality index (CAQI). Specifically, the CAQI was used to measure the comprehensive status of ambient air quality, after which the spatiotemporal distribution of the CAQI and its spatial correlation and clustering were investigated at the month and year levels, respectively. The CAQI values were generally high nationwide, with remarkable spatiotemporal variations. Additionally, cities with higher (or lower) CAQI values were concentrated in north (or south) China, while those with higher CAQI values were also observed in west and east China. The CAQI values exhibited a U-shaped trend from January to December, with the highest values being observed in winter and spring and the lowest during summer. Moreover, particulate matter ($PM_{2.5}$ and PM_{10}) is the major pollutant during most of the year, with $PM_{2.5}$ being prevalent in east and central-south China and PM_{10} in northwest and north China; CAQI values are highly dependent on particulate concentrations. During summer, O_3 becomes a major pollutant and contributes greatly to CAQI, with the highest O_3 being observed in the Bohai Rim, the middle and lower reaches of the Yellow River, and the eastern coast of China. Finally, there was significant spatial autocorrelation and clustering of the CAQI, with spatial hot spots of CAQI being observed in southwest Xinjiang province, where air pollution issues have not received a great deal of attention, as well in Beijing-Tianjin-Hebei (BTH) and its surrounding areas, while cold spots for CAQI are mainly in south and northeast China.

1. Introduction

China has undergone rapid development in various fields over the last few decades; however, this unprecedented growth and prosperity has come with great costs to the environment. Air pollution has become one of the most pressing environmental issues in China (Cai et al., 2017) and will continue to be a major challenge. Air quality in China has drawn extensive attention because of the frequent occurrence of heavy pollution events and the serious harm it causes. Poor air quality not only poses severe threats to human health (Cao et al., 2011; Ding et al., 2017; Duan et al., 2016; Guo et al., 2010; Hao et al., 2017; Lu et al., 2015) but also adversely affects socioeconomic development (Li and Zhang, 2014; Ma and Zhang, 2014; Mu and Zhang, 2013). In fact, air pollution is a complicated problem with various sources and pollutants. Accordingly, a comprehensive understanding of the spatial distribution and temporal variations in air pollution is crucial for developing specific and effective measures of air-quality improvement.

Numerous studies have investigated the spatiotemporal characteristics of different air pollutants in China. Lin et al. (2014) reported that the spatial pattern of $PM_{2.5}$ remained stable from 2001–2010, while high levels of $PM_{2.5}$ were observed in the Beijing-Tianjin-Hebei (BTH) region and east China. Peng et al. (2016) found that $PM_{2.5}$ increased rapidly from 1999 to 2011, especially in central and east China, when areas with $PM_{2.5}$ values exceeding the national standard ($35\,\mu g/m^3$) became larger. Han et al. (2016) found that areas with high occurrences of PM_{10} shifted from central to south and east China during 1961–2012, with the most frequent occurrences being observed in the BTH region, Shanxi, Shaanxi and Henan provinces. Wang et al. (2014b) showed that the concentrations of $PM_{2.5}$, PM_{10}, CO and SO_2 were higher in cities located in the north than in west and southeast China; the number of non-attainment days was highest in winter; and $PM_{2.5}$ has made the greatest contribution to air pollution in China. Based on $PM_{2.5}$ monitoring data from 161 Chinese cities, Li et al. (2016) concluded that the lowest diurnal $PM_{2.5}$ pollution was observed during late spring to early

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autumn, and that is heavy in winter. Using daily PM_{10} data in Beijing from 2008–2012, Hu et al. (2013) showed that PM_{10} pollution in south Beijing was much more serious than that in north Beijing, and that it tended to decline in summer and winter, while increasing in spring. Chen et al. (2015) also pointed out that the air quality in southern and northern Beijing showed completely different spatial patterns, with late night and early morning being the most common time for $PM_{2.5}$, PM_{10}, CO, SO_2, and NO_2 pollution, while O_3 pollution was most serious during the afternoon. Gao et al. (2017) reported that the concentration of O_3 increased by 67%, while that of NO_x decreased by 38% from 2006 to 2015 in urban areas of Shanghai.

Spatial correlation and clustering of air quality in China has also received increased attention. Ma and Zhang (2014) revealed that air pollution shows significant spatial correlation, with aggregation hot spots concentrated in the BTH region and the Yangtze River Delta. Wang and Fang (2016) suggested that urban $PM_{2.5}$ in the Bohai Rim Urban Agglomeration exhibits obvious spatial agglomeration, with the highest (or lowest) hot spots being found in spring (or summer). Based on the $PM_{2.5}$ concentrations observed from 2001 to 2012 in 285 cities, Cheng et al. (2017) showed that China's urban smog demonstrates both apparent spatial autocorrelation and agglomeration. Additionally, Zhang et al. (2017) found significant spatial autocorrelation for haze pollution, low-low clustering in the eastern coast areas, and high-high clustering in the North China Plain and surrounding areas based on the AQI (air quality index) data of 288 cities.

However, previous studies of spatiotemporal patterns and spatial agglomeration of air quality in China have focused on megacities or major cities located in central and east China (i.e., Beijing and Shanghai), provincial capitals, key regions (i.e., BTH and YRD), and the entire nation. Additionally, most studies conducted to date have investigated major pollutants such as $PM_{2.5}$ and PM_{10}. However, few studies have investigated the air quality of cities in west China, and no studies have simultaneously considered or integrated all six criteria pollutants (SO_2, NO_2, CO, O_3, $PM_{2.5}$, and PM_{10}) employed to evaluate Chinese urban air quality according to the National Ambient Air Quality Standards (GB 3095-2012) (MEP, 2012a) and the Technical Regulation on Ambient Air Quality Index (on trial) (MEP, 2012b). Furthermore, a higher spatial resolution is essential to obtain a better and more comprehensive understanding of air pollution at the city level (Zhang and Cao, 2015).

Therefore, we investigated the spatiotemporal patterns and spatial agglomeration of air quality at the city level for 338 cities at the prefectural level or above in China based on simultaneous evaluation of all six criteria pollutants. Specifically, we (1) utilize the comprehensive air quality index (CAQI) proposed and recommended by the Technical Regulation for Ambient Air Quality Assessment (on trial) of China (MEP, 2013a) to investigate 338 cities based on monitoring data of the six pollutants in 2016; (2) present the spatiotemporal variations of the CAQI; (3) explore the distribution of major pollutants and the attainment rates of various pollutants; and (4) test the spatial autocorrelation and clustering of the CAQI and major pollutants using the exploratory spatial data analysis (ESDA) method. In this study, CAQI was used as an indicator to reflect the comprehensive status of urban air quality, which can provide a new and different perspective to help understand the complexity of air pollution and the contribution of various pollutants to air pollution in China. Moreover, our study covers all 338 Chinese cities at or above the prefectural level, while previous studies only investigated a few cities or regions; therefore, our results better reveal differences in air quality among regions with higher spatial resolution.

2. Methodology

2.1. Data sources

This study was based on city level data collected in China in 2016 (excluding Hong Kong, Macau and Taiwan due to data inaccessibility). We analyzed air quality data from 338 cities with state-level monitoring stations. Detailed information describing the monitoring stations is available from the National Urban Air Quality Real-Time Publishing Platform (NUAQRPP) (http://106.37.208.233:20035/).

Since 2013, the Ministry of Environmental Protection of China (MEP) has been publishing real-time hourly and daily concentrations of six criteria pollutants through the NUAQRPP. The data, including the $PM_{2.5}$, PM_{10}, CO, SO_2, NO_2 and O_3 presented in this study, were obtained from the NUAQRPP for the period of January 1, 2016 to December 31, 2016. The monitoring stations have been designated as a mix of urban and background sites, with most being in urban areas, although a few are in suburban and rural areas. Each station contains automated monitoring systems utilized to measure the concentrations of SO_2, NO_2, O_3 and CO according to the National Environmental Protection Standards (HJ 193-2013) (MEP, 2013c), and the $PM_{2.5}$ and PM_{10} according to (HJ 655-2013) (MEP, 2013b).

2.2. Comprehensive air quality index

The comprehensive air quality index (CAQI) is a dimensionless index for description and measurement of ambient air quality that covers six pollutants and provides an effective method for monthly and annual urban air quality comparison among cities (Wang et al., 2014a).

Since January 2013, the MEP has published monthly air quality status of key regions and 74 major cities every month. According to the method used by the MEP (2013a), the CAQI is calculated as described below.

First, the monthly and annual concentration of each pollutant was calculated. Specifically, for each city, the monthly and annual mean concentrations of $PM_{2.5}$, PM_{10}, SO_2 and NO_2, the 95th percentile of daily CO concentration, and the 90th percentile of the daily 8 h maximum O_3 concentration were obtained based on the daily data of each pollutant.

Second, the single index (SI) of each pollutant was calculated.

$$SI_i = C_i/S_i \tag{1}$$

where, SI_i is the single index of pollutant i; C_i is the concentration of pollutant i, if i is $PM_{2.5}$, PM_{10}, SO_2 or NO_2; C_i is the monthly or annual mean concentration, if i is CO or O_3, C_i is the specific percentile concentration; S_i is the national Grade II standard (see Supplementary Table S1) of pollutant i, if i is $PM_{2.5}$, PM_{10}, SO_2 or NO_2, S_i is the Grade II annual concentration, if i is CO, S_i is the Grade II daily concentration, and if i is O_3, S_i is the Grade II daily maximum 8-h concentration.

Third, the CAQI was calculated as follows:

$$CAQI = \sum_i SI_i,(i = PM_{2.5},\ PM_{10}, SO_2,\ NO_2,\ CO,\ O_3) \tag{2}$$

The comprehensive air quality level is negatively correlated with CAQI, with a greater CAQI indicating worse air quality.

Finally, the maximum index (MI) and major pollutant (MP) values were identified.

$$MI = max\{SI_i\},(i = PM_{2.5},\ PM_{10},\ SO_2,\ NO_2,\ CO,\ O_3) \tag{3}$$

If the MI equaled the single index of a certain pollutant and MI > 1, then this pollutant was the MP for a city in a month or year. Moreover, if the single index of a certain pollutant was ≤ 1, the concentration of this pollutant meets the national air quality standard for a city in a month or year.

2.3. Spatial autocorrelation analysis

According to the first law of geography proposed by Tobler (1970), everything is related to everything else, but near things are more related than distant things. This phenomenon is called spatial autocorrelation. The spatial correlation characteristics of atmospheric activity lead to significant spatial autocorrelation for air pollution (Cheng