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Original Research

The Characteristics of Spatiotemporal Distribution of $PM_{2.5}$ in Henan Province, China

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Abstract

$PM_{2.5}$ is the top issue of air pollution in Henan Province in China, especially in autumn and winter. In order to investigate its spatial and temporal distribution characteristics, monitoring data were collected in 17 cities and analyzed by using statistical methods and GIS tools. The results show that 57.16% of the entire days in 2015 met Chinese the national standard on the daily average concentration of $PM_{2.5}$ in those 17 cities. However, 73.68% of the days in winter, 44.37% of the days in spring, 34.53% of the days in autumn, and 20.08% of the days in summer failed to meet the standard. Analysis shows the average concentration of $PM_{2.5}$ on weekends was 8.04% higher than that of working days. The fact that the value of $PM_{2.5}/PM_{10}$ was between 0.50 and 0.65 and that there was a high relevance between the $PM_{2.5}$ concentration and SO_2 concentration suggests that the main air pollutants are coarse particles that are mainly released by coal burning. The positive correlation between $PM_{2.5}$ and NO_2 reveals that vehicle exhaust emissions is another main reason for air pollution. Owing to the influence of the temperature and sunlight changes, the correlativity of $PM_{2.5}$ concentrations and O_3 concentrations presents a remarkable difference in different seasons. The correlation coefficients are 0.003 for spring, 0.496**(p = 0.01) for summer, -0.353*(p = 0.05) for autumn, and -0.315*(p = 0.05) for winter, respectively. The method proposed in this paper has been verified and the research result is helpful for making relevant environmental policy.

Keywords: $PM_{2.5}$, Henan Province, heavy haze polluted days, correlation

Introduction

With the rapid process of economic development, industrial expansion, and urbanization in the past few decades in China, environmental problems are becoming more and more serious. Among them, $PM_{2.5}$ pollution is of particular concern and has been a hot issue recently. Secondary pollution of regionalized dust-haze has occurred frequently in the Yangtze River Delta (YRD), Pearl River Delta (PRD), and Beijing-Tianjin-Hebei (BTH) regions in recent years [1-5]. Plenty of research on elemental composition [6], source apportionment [7-10], and health effects [11-12] of $PM_{2.5}$ have been conducted. According to data from the national urban air quality real-time publishing platform of China's environmental monitoring station in China, Henan Province has been one of the most polluted areas across the country. Unfortunately, there are few studies carried out on the spatiotemporal distribution characteristics of $PM_{2.5}$ pollution at present, and its formation mechanism is not yet clear. Therefore, it is very important to study the characteristics of the

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spatiotemporal distribution of $PM_{2.5}$ concentrations and analyze the pollution factors' correlation.

Pollutants Data and Analysis Methods

This paper presents one of the first long-term data sets including a statistical summary of $PM_{2.5}$ concentrations as collected from the national urban air quality real-time publishing platform. A national air quality monitoring network with nearly 950 monitoring stations in 190 Chinese cities was put into operation at the end of 2013 for publishing real-time monitoring data on air quality such as $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3 for the public [13]. In this study, the characteristics of spatial and seasonal distribution of $PM_{2.5}$ in 17 pollution-monitoring cities (except Jiyuan) were researched thoroughly in Henan Province in 2015 (Fig. 1). In addition, the weekend and workday effects in Henan will be discussed. Finally, the correlation of $PM_{2.5}$ and other pollutants will be analyzed. Because some cities lacked monitoring data of $PM_{2.5}$ concentration in December 2014, the period of four 2015 seasons are assigned as follows: winter is from January to February, spring is from March to May, summer is from June to August, and autumn is from September to November.

To analyze and visualize $PM_{2.5}$ pollution datasets, a geographical database was built with GIS software tools. The database contains three layers, including provincial border, city border, and monitoring cities. The collected pollutant data include $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3. In addition to summary statistics, the collected datasets were analyzed using the correlation analysis method. The outline of research can be depicted in Fig. 2.

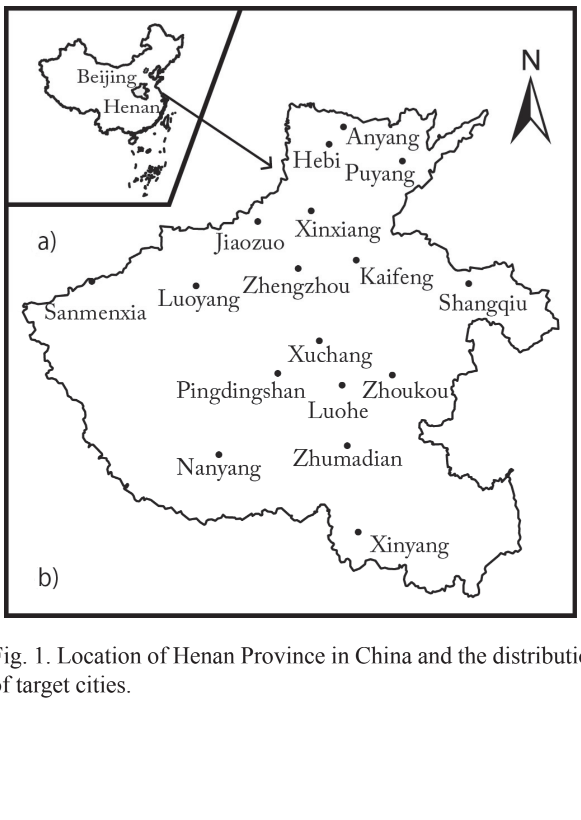

Fig. 1. Location of Henan Province in China and the distribution of target cities.

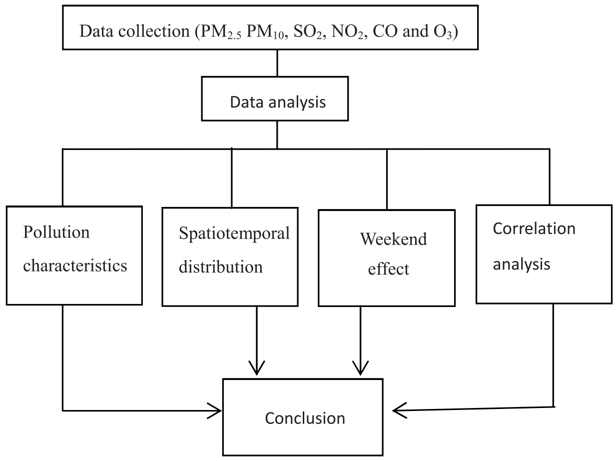

Fig. 2. The outline of research.

Results and Discussion

Monthly Characteristics of $PM_{2.5}$ Pollution

To explore the characteristics over a full year, a monthly data distribution diagram was created. The new national ambient air quality standards of China (NAAQS) requires that the 24-hour average $PM_{2.5}$ concentration upper limits be 35 μg/m³ for grade I and 75 μg/m³ for grade II, respectively. WHO standards of $PM_{2.5}$ concentration limits for the 24-hour average is 25 μg/m³. Fig. 3 shows the rates of days exceeding the limit of $PM_{2.5}$ average concentration according to WHO and NAAQS.

The $PM_{2.5}$ concentration data in 2015 was summarized. The values cover the range 11.8-548.8 μ g/m³. The average concentration was 80.04μg/m³. The ratio of days exceeding the limit of NAAQS was 42.84% in 2015 when referring to the NAAQS grade II (75μg/m³) when referring to the NAAQS grade I (35 μg/m³), ratio of days exceeding the standard limit was 86.49% in 2015, and the highest and lowest ratios were 98.86% in January and 72.49%

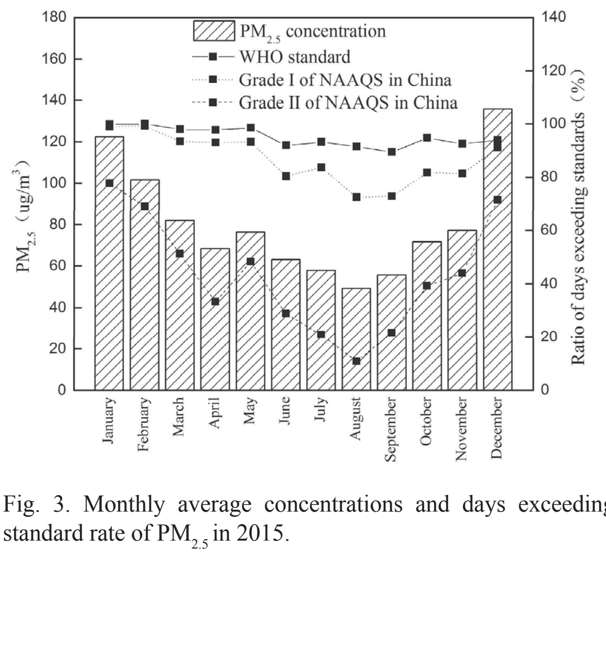

Fig. 3. Monthly average concentrations and days exceeding standard rate of $PM_{2.5}$ in 2015.

in August. However, when referring to the limit of the 24-hour average of the WHO standard (25 μg/m³), the ratio of days exceeding the standard was 94.81% in the year, and the highest ratio was 100% in February. From the statistical data above, $PM_{2.5}$ pollution is extremely serious, especially in winter.

Spatiotemporal Distribution Characteristics of $PM_{2.5}$

Generally, $PM_{2.5}$ concentrations show a remarkable seasonal variability with the highest during the winter and the lowest during the summer (Fig. 4).

The ratio of days exceeding the standard of $PM_{2.5}$ concentrations was 73.68% in winter when referring to NAAQS for the 24-hour average of grade II (75 μg/m³). High $PM_{2.5}$ concentration in wintertime is associated with enhanced anthropogenic emissions from fossil fuel combustion and unfavorable meteorological conditions for pollutant dispersion. Besides, the accumulation of primary emissions, new particle formation, and secondary production of both the inorganic aerosols and organic matters could further enhance fine PM abundance [14-16]. Zhengzhou and Anyang were the two worst-polluted cities in winter as shown in Fig. 4d), and the ratios of exceeding standards were 88.14% and 84.75%, respectively. The air quality of Zhengzhou and Anyang was not only due to the primary emissions from local sources such as industrial and agricultural sources but also due to the regional transported contribution (e.g., from nearby Shanxi Province and Shandong Province) and secondary production. Furthermore, the climate of Henan is characterized by stagnant weather with weak wind and relatively low boundary layer height,

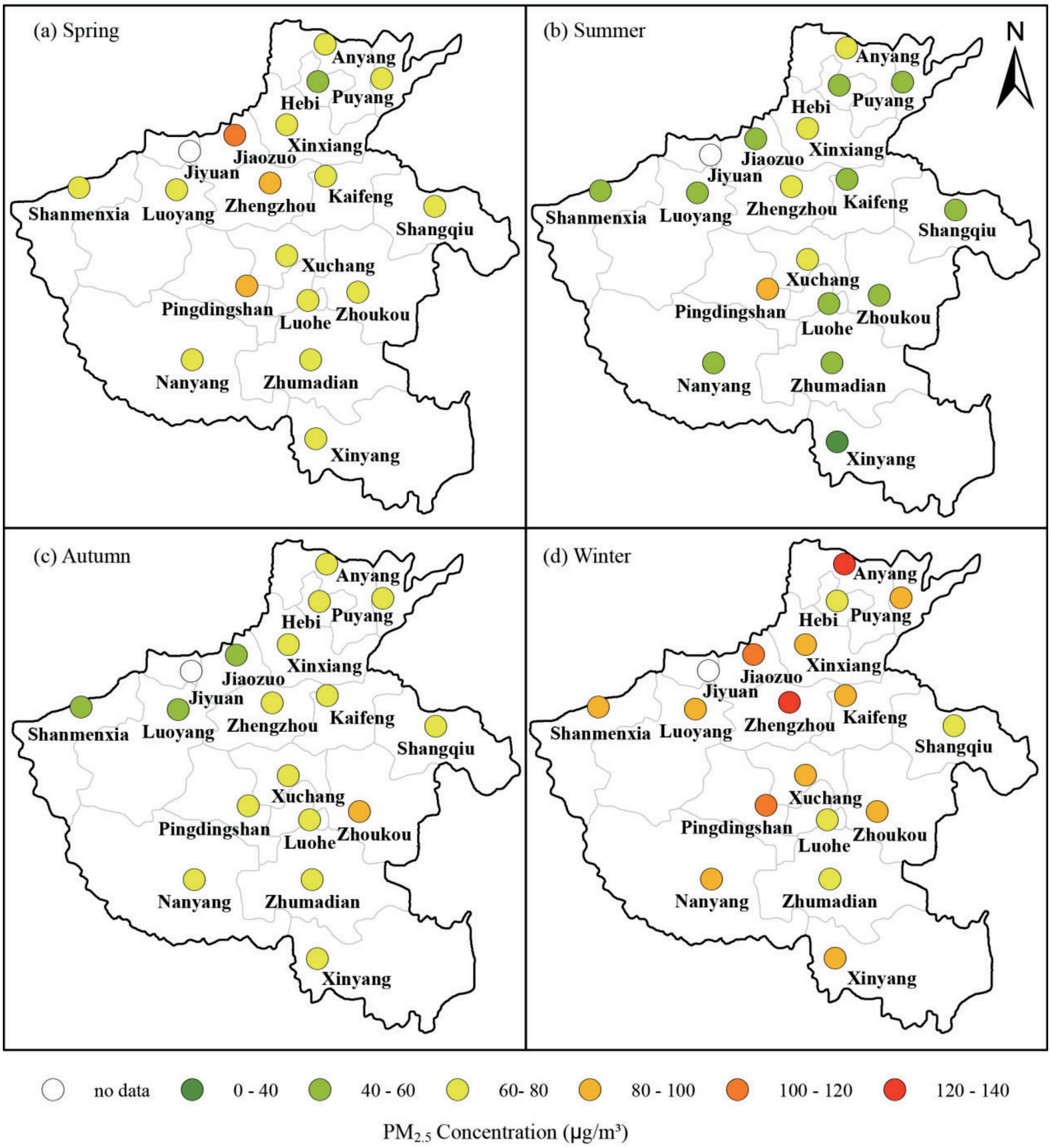

Fig. 4. $PM_{2.5}$ spatial distribution of Henan Province in the four seasons of 2015.

leading to the favorable atmospheric conditions for accumulation, formation, and processing of aerosols [17]. For example the Siberian cold snap has a big influence on Henan Province, especially in winter. The lowest $PM_{2.5}$ concentration was observed in Xinyang, a southwest city of Henan, which has fewer coal-based industries and good dispersion weather conditions.

Air quality conditions in spring are slightly better than winter. The average concentration of $PM_{2.5}$ is 75.57 μg/m^{3}in spring and the ratio of days exceeding standards is 44.37%. Plants can absorb atmospheric particulates, and this plays an important role in reducing particulate matter pollution [18]. Moreover, the plant purification rate was high in summer and autumn and low in spring and winter [19]. Considering that plants are growing in spring, plant density is small [19] and the ability to purify is weak. Meanwhile, the atmosphere is relatively stable in spring, which is not good for contaminant diffusion [13, 20]. Therefore air quality improved slightly, but was still serious in spring (Fig. 4a).

The air condition in summer was better than the other seasons in 2015 (Fig. 4b). Because of a lot of rainfall in summer, the particulate matter in the air can be washed out [21-22]. In addition, the vegetation coverage enlargement in summer can help clean air as well [23]. The daily average concentration was 56.65 μg/m^3 and the ratio of days exceeding standards was 20.08%. The air quality in summer 2015 was best when compared with the other three seasons. This conclusion is in accordance with the result of Li et al. [24].

Average concentration of $PM_{2.5}$ was 68.20 μg/m^3 in autumn 2015, and the ratio of days exceeding standards was 34.52%. Zhoukou was the most seriously polluted city in the autumn in Henan as shown in Fig. 4c). According to historic statistical records, the region of Zhoukou is a traditional agricultural area. The relatively high $PM_{2.5}$ levels during the autumn in this city were due to large-scale open biomass burning during the agricultural harvest season [13]. At the same time, the atmospheric conditions are not good for diffusion of contaminant, and this also worsens air quality. Therefore, during the peak period of harvest (from October 2 to October 6), the average concentration of $PM_{2.5}$ was 151.1μg/m^3, which is two times as high as the standards for the 24-hour average of NAAQS Grade II (75 μg/m^3). Consequently, from the data above, the $PM_{2.5}$ pollution became worse after entering the autumn, and large-scale biomass burning could worsen air quality remarkably.

Weekend Effect and Workday Effect

It is generally acknowledged that the human activities and industrial production intensity on workdays will be higher than the weekends, thus the workdays may produce more contaminants in the air, which can lead to higher concentrations of pollutants on workdays than on weekends. This is commonly known as the "weekend effect" [25].

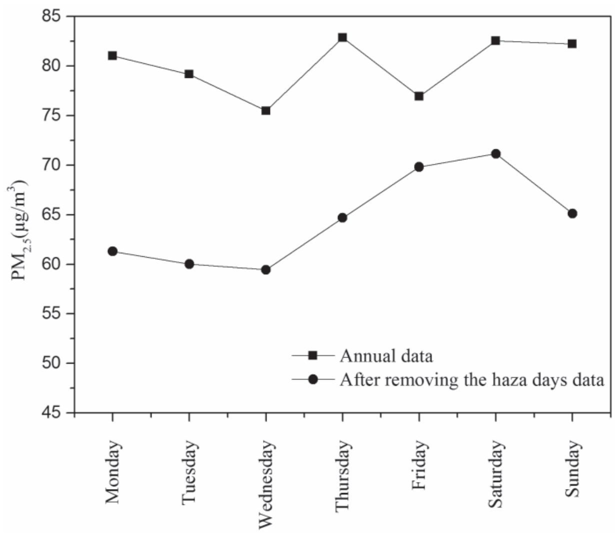

Fig. 5. Weekly variation of PM2.5 concentrations.

In order to explore the pollution characteristics of $PM_{2.5}$ between workdays and weekends in Henan we carried out an analysis of hebdomad distribution. Fig. 5 shows the hebdomad distribution of the $PM_{2.5}$ concentration in 2015. From Fig. 5 we can see that the $PM_{2.5}$ concentration does not show regular variation characteristics in the year. When the extremely polluted days due to heavy haze controlled mainly by meteorological conditions have not been taken into consideration, the average concentration of $PM_{2.5}$ on the weekend is 8.05% higher than the workdays, and it does not reveal a clear weekend effect and noticeable inverse weekend effect. The reasons for this are considered as follows. On the one hand, the extremely high concentration of $PM_{2.5}$ during heavily polluted days may cause irregular results. On the other hand, many factories in small and medium cities continue producing activities on the weekend due to a relaxed weekend rest system.

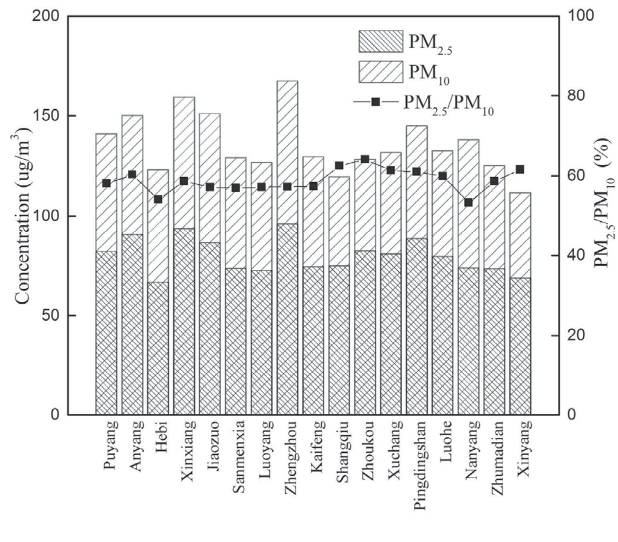

Fig. 6. Daily concentrations and ratios of $PM_{2.5}$ and PM_{10}.

Correlativity between $PM_{2.5}$ and Other PM_{10} Pollutants

Secondary particulate matter plays an important role in $PM_{2.5}$ concentrations, and flying dust and coal-burning dust make a great contribution to PM_{10} concentrations [16, 26-27]. Therefore, in order to study the pollution characteristics of the research area we compares 17 cities' ratios of $PM_{2.5}$ concentrations and PM_{10} concentrations from January to December 2015. Generally, the smaller the ratio, the greater the possibility that the research area can see traditional coal pollution.

Fig. 5 shows the ratio of $PM_{2.5}$ and PM_{10} among the 17 cities in Henan. We can divide these figures into three categories: Nanyang and Hebi under the ratio of 0.55, Zhoukou and Shangqiu above the ratio of 0.62, the other cities in the range of 0.55-0.62. The average of ratio of $PM_{2.5}$ and PM_{10} is 0.588 in Henan province in 2015, close to the nationwide ratio of 0.591 [24]. The result in Henan is smaller than the ratio of the east coast in the United States (0.68 [28]) and Guangzhou (0.85[29]). This study shows that coarse particles play an important role in Henan Province.

Correlativity between $PM_{2.5}$ and Other Pollutants

Table 1 shows the correlation coefficient of $PM_{2.5}$ and SO_2, CO, NO_2, and O_3. SO_2 is the major precursor of secondary particles that are mainly emitted by factories and coal-fired powerplants. The significant relationship between SO_2 and $PM_{2.5}$ indicates that sulfuric acid-type pollution is serious in Henan Province. Long et al. [30] found that the CO concentration – which is mainly from automobile exhaust and $PM_{2.5}$ concentration in the atmosphere – have significant correlation in Guangzhou.

This study finds that $PM_{2.5}$ and CO also have a strong correlation in Henan Province, thus this implies that automobile exhaust pollution contributed largely to the air pollution in Henan. NO_2 mainly comes from biomass burning and fossil fuel combustion emissions, industrial and agricultural production, natural physical and chemical reactions, atmospheric transport, and so on [31-32]. NO_2 will generate secondary particles by atmospheric chemical reactions, which will realize the phase transformation from gas to particle matter. The correlation between $PM_{2.5}$ concentration and NO_2 concentration is significant in Henan, which shows that industrial production and automobile exhaust NO_2 emissions have a serious impact on air quality. CO, NO_2, and O_3 are the main substances in the photochemical reaction, which has an important contribution to the formation of the secondary particle [33]. Therefore, its concentration and the concentration of $PM_{2.5}$ show correlation to some extent. CO and NO_2 have a positive correlation; meanwhile, the concentrations of $PM_{2.5}$, and O_3 have a negative correlation with the concentration of $PM_{2.5}$.

Table 1.The correlation of $PM_{2.5}$ and the pollution index.

Number	City	PM_{10}	SO_2	CO	NO_2	O_3
1	Puyang	0.937**	0.932**	0.874**	0.912**	-0.755**
2	Anyang	0.961**	0.962**	0.889**	0.869**	-0.682*
3	Hebi	0.867**	0.694**	0.877**	0.719**	-0.776**
4	Xinxiang	0.982**	0.784**	0.939**	0.861**	-0.747**
5	Jiaozuo	0.991**	0.862**	0.563	0.600*	-0.375
6	Sanmenxia	0.944**	0.849**	0.845**	0.829**	-0.754**
7	Luoyang	0.980**	0.926**	0.649*	0.757**	-0.601*
8	Zhengzhou	0.941**	0.926**	0.879**	0.681*	-0.770**
9	Kaifeng	0.938**	0.890**	0.948**	0.890**	-0.652*
10	Shangqiu	0.974**	0.854**	0.917**	0.741**	-0.668*
11	Zhoukou	0.974**	0.885**	0.741**	0.833**	-0.828**
12	Xuchang	0.968**	0.826**	0.749**	0.806**	-0.635*
13	Pingdingshan	0.856**	0.917**	0.355	0.439	-0.217
14	Luohe	0.925**	0.859**	0.804**	0.843**	-0.354*
15	Nanyang	0.918**	0.784**	0.847**	0.553	-0.706*
16	Zhumadian	0.957**	0.640**	0.921**	0.864**	-0.684*
17	Xinyang	0.985**	0.666*	0.790**	0.850**	-0.574

*Significant correlation at 0.05 level (bilateral) **Significant correlation at 0.01 level(bilateral)

Except for the cities of Jiaozuo and Pingdingshan, the concentrations of $PM_{2.5}$ and CO, NO_2, and O_3 have a significant relation characteristic in the other 15 cities in Henan (Table 1), which illustrates that particulate matter produced by secondary pollutants have a larger proportion. Then Jiaozuo and Pingdingshan are typical traditional coal-burning cities with lots of heavily polluting enterprises [34-35] in them, and particulate matter is mainly produced by a primary pollution source. This can explain that the correlation is not significant in them.

The trend of O_3 pollution will be aggravated in our country [34, 36]. In order to explore the relationship between $PM_{2.5}$ and O_3 ,we studied the correlation in the four seasons from December 2014 to November 2015. The correlation of $PM_{2.5}$ and O_3 are -0.315*,-0.353*, 0.496**, and 0.003 in the winter, autumn, summer, and spring, respectively. Because low temperature, relatively weak light, slow photochemical reaction in autumn and winter, and increased particulate matter hinder the illumination to some extent, which makes a great effect on the process of photochemical reaction [37], $PM_{2.5}$ and O_3 present negative correlation. Coal burning for heat is always stopped in summer, during which the concentration of particulate matter is significantly reduced by strong sunlight illumination, high temperature, and more intensive photochemical reaction in summer. At the same time [33], the concentration of particulate matter formed by the secondary pollution source increased, so the correlation between $PM_{2.5}$ and O_3 prevents the positive.

Conclusions

Based on long-term data collection of $PM_{2.5}$ and other pollutants, the spatiotemporal distribution of $PM_{2.5}$ was examined. The correlativity between pollutants and the weekend effect was explored and investigated. The conclusions are as follows:

1. 57.16% of all days in 2015 met the daily average concentration of $PM_{2.5}$ standard in those 17 cities when referring to the NAAQS. Particulate matter pollution is serious in Henan Province.
2. $PM_{2.5}$ concentrations show a remarkable seasonal variability, with the ratio of exceeding standards of $PM_{2.5}$ concentrations being winter>spring>autumn>summer.
3. Removing heavily foggy and hazy days, we find that the average concentration of $PM_{2.5}$ in the weekend is 8.05% higher than the workdays, which proves the “inverse weekend effect.”
4. The average ratio of $PM_{2.5}$ and PM_{10} is 0.588 in Henan Province in 2015, which shows that coarse particles play an important role in Henan Province.
5. The relative coefficient of $PM_{2.5}$ and SO_2, CO, NO_2, O_3 first show that sulfuric acid-type pollution is serious in Henan Province; secondly, industrial enterprises and automobile exhaust emissions NO_2 have a serious impact on air quality; and thirdly, there is a certain degree of photochemical pollution in Henan.

Acknowledgments

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