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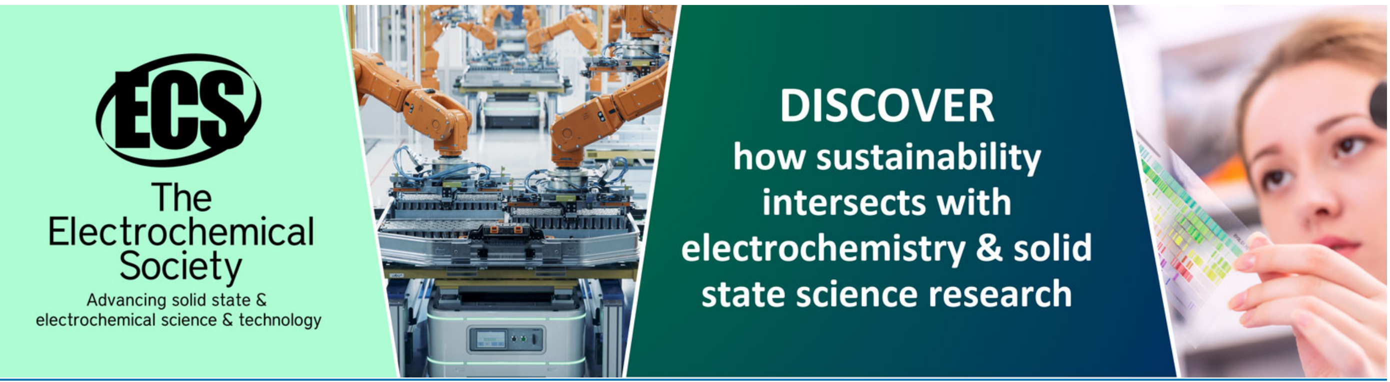

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A Study on Spatial-temporal Distribution Characteristics of $PM_{2.5}$ Concentrations in Nanjing during 2012-2016

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Abstract. Spatial-temporal distribution characteristics of $PM_{2.5}$ concentrations in Nanjing is explored based on the $PM_{2.5}$ data obtained by 9 automatic air quality monitoring stations in the city during 2012-2016.The results show that: 1)$PM_{2.5}$ concentrations were in a downward trend in the recent 5 years, but there were still some over-standard conditions in individual years; 2) among the different types of monitoring stations, the highest $PM_{2.5}$ concentrations were obtained at the traffic stations, followed by the urban stations, the control station, and the suburban stations successively; 3) from the perspective of temporal distribution, the highest $PM_{2.5}$ concentrations were observed in winter, followed by spring, autumn, and summer successively; 4) monthly average $PM_{2.5}$ concentrations followed a U-shaped distribution on the whole; 5) from the perspective of spatial distribution, $PM_{2.5}$ concentrations in the recent 5 years had the characteristic of being higher in the north and central region and lower in the south; 6) there were significant positive correlations between $PM_{2.5}$ concentrations and NO_2 and SO_2 concentrations, indicating that precursors have significant influence on $PM_{2.5}$ concentration.

1. Introduction

With the rapid progress of urbanization, particulate matters have become the primary air pollutants in cities of China. $PM_{2.5}$ would be inhaled into the lungs easily due to their small size, and as a result, they may induce respiratory system diseases, cardiovascular diseases, cancers, and lesions. This issue has attracted extensive attention from scholars[1]. Nanjing is an economically and politically developed city of China with dense population and intensive industry, and is facing serious air pollution. In 2016, the national grade II air quality standard reached for 236d in the urbanization area of Nanjing, and the primary pollutant was $PM_{2.5}$. The standard-reaching rate was 65.6%, increasing by 1.2% on year-on-year basis, but there is still a long way to meet the target – 80%. Huang Liming et al. studied $PM_{2.5}$ pollution in 5 typical functional zones of Nanjing in winter, spring, and autumn of 2001, and the results showed that the over-standard rates for PM_{10} and $PM_{2.5}$ in Nanjing were 72% and 90% respectively[2]. Analysis of sources of atmospheric particulates in Nanjing showed that, among the sources of $PM_{2.5}$ in Nanjing in 2013, contribution rates of industry, motor vehicle exhaust, flying dust, and other pollution sources were 46.4%, 24.6%, 14.1%, and 14.9% respectively. According to the results of numerical air quality simulation, $PM_{2.5}$ contribution rate of regional transport in Nanjing is within the range of 19.6%-37.9%, averaging at 28.5%.Currently, multiple-station and long-term observation of $PM_{2.5}$ concentrations in Nanjing is lacking. This study analyzed the $PM_{2.5}$ data obtained by automatic air quality monitoring substations of 9 monitoring stations in Nanjing during 2012-2016, and worked out the temporal and spatial distribution characteristics of $PM_{2.5}$ concentrations in the city as well as the

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relation between $PM_{2.5}$ and other atmospheric pollutants (SO_2 and NO_2), thus providing a scientific basis for air pollution control in Nanjing.

2. Study areas and methods

2.1. Selection of study areas
Because environmental monitoring stations in Nanjing are few in number and intensively distributed, Liuhe District in the north and Gaochun District and Lishui District in the south were excluded from this study to improve the accuracy of the conclusions.

2.2. Distribution of stations
During 2012-2016, Nanjing Environmental Monitoring Center carried out real-time air quality monitoring at 9 monitoring stations, which are classified into four types by function: urban environmental assessment station (urban station for short, including Caochang Gate Station, Shanxi Road Station, Ruijin Road Station, and Olympic Sports Center Station), dense traffic assessment station (traffic station for short, including Zhonghua Gate Station and Maigao Bridge Station), suburban environmental assessment station (suburban station for short, including Pukou Station and Xianlin University Town Station), and environmental control station (control station for short, including Xuanwu Lake Station).

2.3. Instruments
Thermo Fisher 1405F monitoring instrument was used to monitor $PM_{2.5}$.Thermo Fisher 42 Cchemiluminescent NO-NO_2-NO_x analyzer was used as the NO_x analyzer, whose lowest detectable limit is 0.05×10-9 (volume fraction);null drift: less than 0.025×10-9/24 h; span drift: ±1%/24 h. Thermo Fisher 43i ultraviolet fluorescent pulse analyzer was used as the SO_2 monitor, whose lowest detectable limit is 0.5×10-9 (volume fraction); accuracy: 1×10-9 (volume fraction); null drift: less than 1×10-9/24 h; span drift: ±0.5%/24 h. These instruments were all calibrated regularly using calibrators according to national standards to guarantee the accuracy and effectiveness of monitoring data.

All the instruments output data in 5-minute intervals. The hourly average is the arithmetic mean value of all the 5-minute data in an hour. All the data in this analysis was obtained based on hourly average concentrations. The daily average concentration is the arithmetic mean value of 24 hourly average concentrations in a day. The monthly average concentration is the arithmetic mean value of daily average concentrations of all the days in a month. The seasonally/yearly average concentration is the arithmetic mean value of monthly average concentrations of all the months in a season/year.

3. Results and analysis

3.1. Interannual variations of $PM_{2.5}$ concentrations
The yearly average $PM_{2.5}$ concentration in Nanjing during 2012-2016 first increased and then decreased. During 2012-2013, the yearly average $PM_{2.5}$ concentration increased from 61$\mu g \cdot m^{-3}$ to 77.1$\mu g \cdot m^{-3}$.After that, the concentration dropped year by year to 47.6$\mu g \cdot m^{-3}$ in 2016, decreasing by 38.3% (Fig.1). According to GB3095-2012 - AAQS (ambient air quality standard), the grade II PM2.5 limit is 35$\mu g \cdot m^{-3}$. That is to say the $PM_{2.5}$ concentration in 2016 exceeded the standard by 36%, and ambient air pollution is still a serious problem in the city.

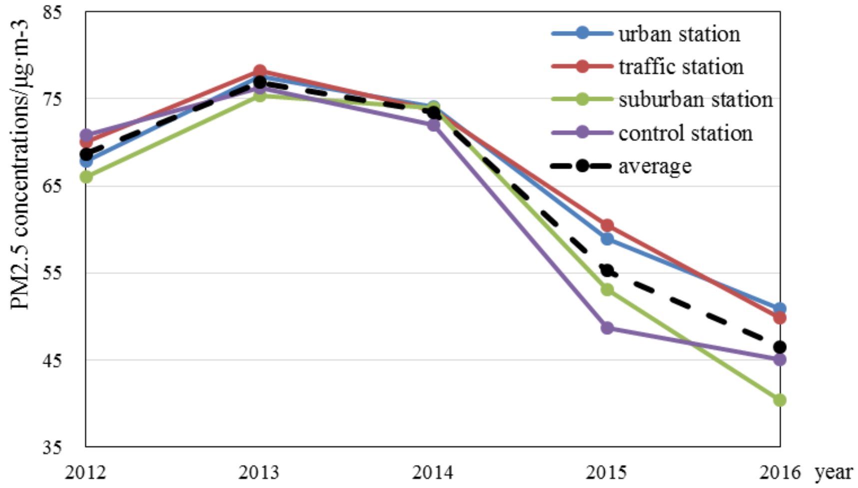

Figure 1. Yearly average $PM_{2.5}$ concentrations at four types of monitoring stations

Among the different types of monitoring stations, the highest $PM_{2.5}$ concentration(five-year average) was obtained at the traffic stations due to the influence of road dust and secondary transformation of gaseous pollutants[3], reaching up to 66.45μg·m^{-3}, closely followed by the urban stations (65.84μg·m^{-3}, the high value may be related to the large people flow); the concentrations were relatively low at the suburban stations and the control station, being 61.78μg·m^{-3} and 62.56μg·m^{-3} respectively.

3.2. Seasonally average $PM_{2.5}$ concentrations

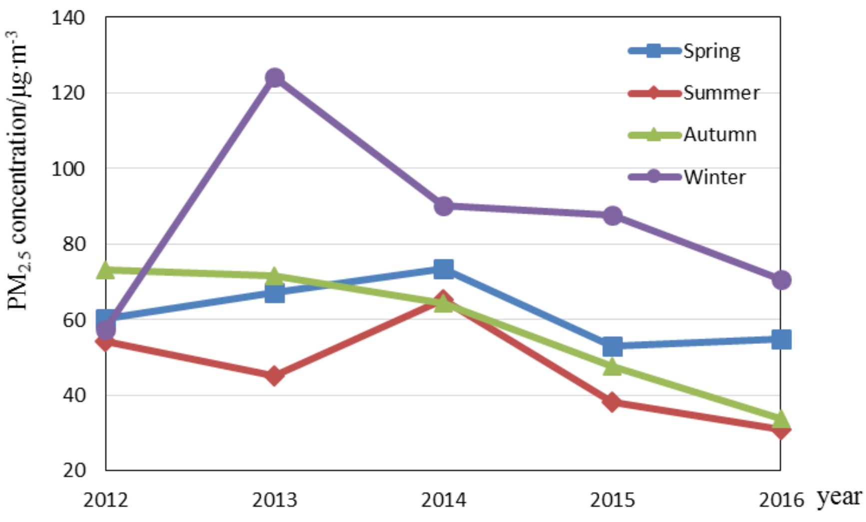

Figure 2. Seasonally average PM2.5 concentrations during 2012-2016

Fig.2 shows the seasonal variations of $PM_{2.5}$ concentrations in Nanjing during 2012-2016. In 2012, the highest $PM_{2.5}$ concentration was 73.2μg·m^{-3}, which was observed in autumn, and the difference between the highest value and the lowest value (in summer) was only 18.9μg·m^{-3}, with small fluctuations across the seasons. During 2013-2016, $PM_{2.5}$ concentrations in winter were all significantly higher than those in the other 3 seasons. The 5-year average $PM_{2.5}$ concentration in winter was 86.1μg·m^{-3}, 1.39 times higher than that in spring, 1.84 times higher than that in summer, and 1.48 times higher than that in autumn. Meanwhile, the $PM_{2.5}$ concentrations in spring during 2014-2016 were higher than those in summer and autumn, and concentrations in summer and autumn were close to each other. The possible reasons are described as below. Windy weather in winter and spring would increase ground dust and fine PM concentration. Radiation inversion is common in winter, and the poor vertical convection and weak horizontal winds are bad for outward diffusion and dilution of suspended particulate matters. In addition, winter and spring contain heating months, during which consumption of fossil fuel would increase, thus leading to the increase in discharge of $PM_{2.5}$ and other pollutants.

3.3. Monthly variations of $PM_{2.5}$ concentrations.

On the whole, the monthly average $PM_{2.5}$ concentrations during 2012-2016 followed a U-shaped distribution, with the valley appearing in July, August, and September, and the peak in November, December, and January (Fig.3).The monthly average concentration in December 2013 was the highest (158.4μg·m^{-3}),closely followed by the concentration in January 2013 (132.2μg·m^{-3}). Coal consumption in the heating season greatly contributed to the high values. The monthly average concentration in October 2016 was the lowest (24.7μg·m^{-3}), closely followed by the concentration in August 2016 (25.8μg·m^{-3}), and this may be because there is more rain in summer. As can be seen in the figure, there is a peak in June of 2012-2014, and this may be because there is much haze weather at the end of spring and the beginning of summer[4].

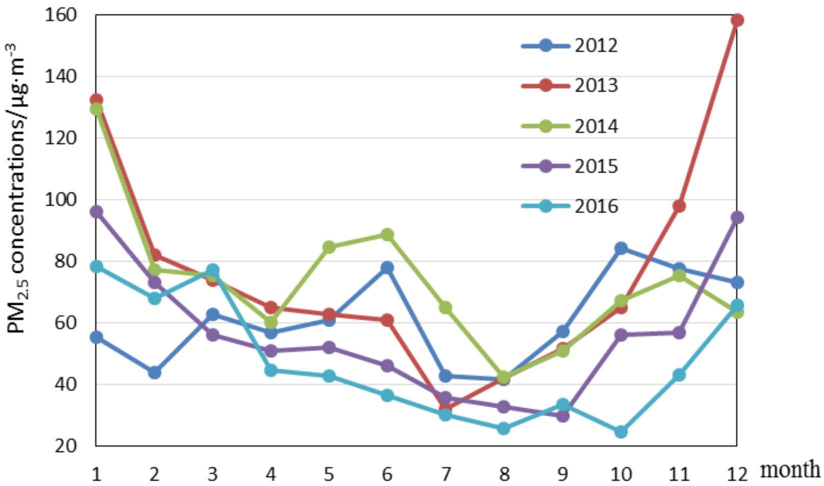

Figure 3. Monthly average $PM_{2.5}$ concentrations during 2012-2016

4. Spatial distribution characteristics of $PM_{2.5}$ concentrations

Kriging interpolation is a method for unbiased optimal estimation of variables in a finite region based on theoretical analysis of semivariable function[5-6].To avoid the problem of large errors in Kriging interpolation results, which were caused by the lacking and uneven distribution of monitoring stations, NDVI (Normalized Difference Vegetation Index) and building density were treated as independent variables and fitted with $PM_{2.5}$ concentration in the establishment of relational model. Spatial distribution of $PM_{2.5}$ concentration was then obtained through inversion using historical NDVI values and building density values. Meanwhile, Liuhe District, Gaochun District and Lishui District, where there were no monitoring stations, were excluded from the study areas to guarantee the credibility of the inversion results.

The NDVI values used in this paper were from remote-sensing images provided by MODIS, and ENVI5.1 was used to extract the data at the monitoring stations and in the corresponding time periods. Google historical satellite maps were supervised and classified, and the focal statistics tool of ArcGIS10.2 was used to obtain the building density graphs. Then, building density data was extracted according to the coordinates of the monitoring stations.

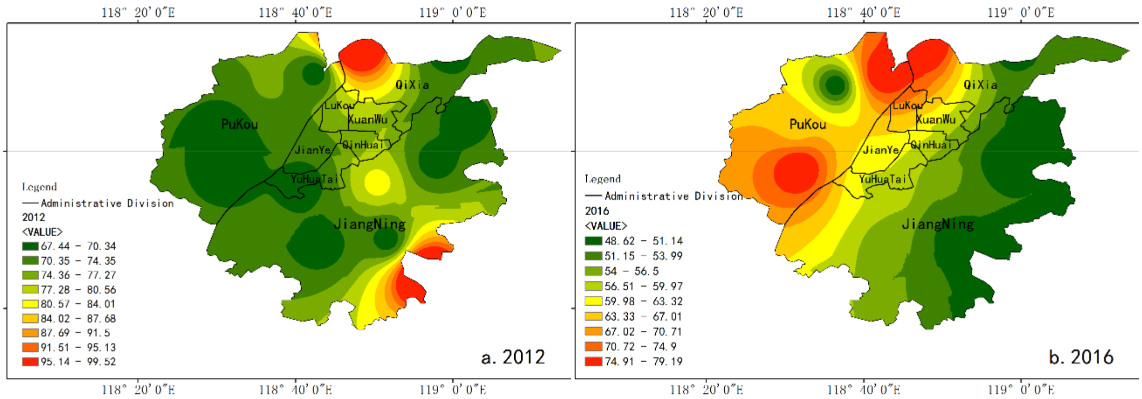

Figure 4. Spatial distribution of $PM_{2.5}$ concentrations in Nanjing during 2012-2016 obtained by using interpolation method

Spatial distribution of $PM_{2.5}$ concentrations in Nanjing during 2012-2016 was obtained by using the Kriging interpolation method (Fig.4).On the whole, the distribution of $PM_{2.5}$ concentration in Nanjing had the characteristic of being higher in the north and central region and lower in the south. The $PM_{2.5}$ concentration obtained through interpolation was obviously higher in the north of Qixia District and Pukou District and in the central area of Jiangning District. This distribution pattern reflects the influence of industrial layout on $PM_{2.5}$ concentration in Nanjing. There are a few large industrial zones in the north of Qixia District and Pukou District and in the central-western Jiangning District. In addition, high people flow, traffic volume, and emission of suspended particulate matters in the central downtown may deteriorate air quality in Nanjing under adverse weather conditions.

5. Correlation between PM2.5 and precursors

Secondary pollutants generated in the process of migration and transformation of gaseous pollutants (like SO_2 and NO_2) are major chemical constituents of $PM_{2.5}$. Therefore, concentrations of the gaseous pollutants have great influence on $PM_{2.5}$ concentration. This study carried out a correlation analysis between hourly concentrations of $PM_{2.5}$ and SO_2/NO_2. First, K-S (Kolmogorov-Smirnov) statistical tests were made for all groups of data, and Pearson correlation analysis was then carried out (Table 1).

The results showed that $PM_{2.5}$ concentrations at all the stations were significantly and positively correlated with NO_2 and SO_2 concentrations, proving that secondary transformation of precursors has significant influence on $PM_{2.5}$ concentration. Coefficients of correlation between $PM_{2.5}$ concentration and NO_2/SO_2 concentrations at different stations were very close to each other. As can be seen from the results of the correlation analysis, $PM_{2.5}$ concentrations at the urban stations and control station were more influenced by NO_2 concentration, while $PM_{2.5}$ concentrations at the traffic stations and suburban stations were more influenced by SO_2 concentration.

Table 1. Correlation coefficients between $PM_{2.5}$ and SO_2/NO_2 during 2012-2016

Stations	Pollutants	SO_2	NO_2	$PM_{2.5}$
	SO_2	1	0.553*	0.805*
Urban stations	NO_2	0.553*	1	0.817*
	$PM_{2.5}$	0.805*	0.817*	1
	SO_2	1	0.563*	0.823*
Traffic stations	NO_2	0.563*	1	0.735*
	$PM_{2.5}$	0.823*	0.735*	1
	SO_2	1	0.762*	0.802*
Suburban stations	NO_2	0.762*	1	0.793*
	$PM_{2.5}$	0.802*	0.793*	1
Control station	SO_2	1	0.59*	0.582*
	NO_2	0.599*	1	0.675*

$PM_{2.5}$	0.582*	0.675*	1

* means the concentrations were significantly correlated at the level of 0.01 (two-sided).

6. Conclusions

(1)$PM_{2.5}$ concentrations were generally in a downward trend during 2012-2016, dropping to 47.6μg·m^{-3} in 2016, which was still much higher than the national grade II $PM_{2.5}$ limit (35μg·m^{-3}), exceeding by 36%.Among the different types of monitoring stations, the highest $PM_{2.5}$ concentrations were obtained at the traffic stations, followed by the urban stations, the control station, and the suburban stations successively.

(2)The highest $PM_{2.5}$ concentrations in Nanjing were observed in winter, followed by spring, autumn, and summer successively, with the 5-year averages in the seasons being 86.1μg·m^{-3}, 61.8μg·m^{-3}, 58.2μg·m^{-3}, and 46.8μg·m^{-3} respectively.

(3)On the whole, the monthly average $PM_{2.5}$ concentrations in Nanjing followed a U-shaped distribution, with the valley appearing in July, August, and September, and the peak in November, December, and January. The monthly average concentration in December 2013 was the highest (158.4μg·m^{-3}), and the monthly average concentration in October 2016 was the lowest (24.7μg·m^{-3}).

(4)The distribution of $PM_{2.5}$ concentration in Nanjing during 2012-2016 had the characteristic of being higher in the north and central region and lower in the south. The concentration in the central downtown was relatively high due to the influence of industrial layout and high traffic flow.

(5)There were significant positive correlations between $PM_{2.5}$ concentrations and NO_2 and SO_2 concentrations at all the stations, indicating secondary transformation of precursors has significant influence on $PM_{2.5}$ concentration.

Acknowledgments

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