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Spatiotemporal Variations of $PM_{2.5}$ Concentration and Relationship with Other Criteria Pollutants in Nanjing, China

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ABSTRACT

In order to make full use of national monitoring sites data, the variations of mass concentrations of $PM_{2.5}$ and other criteria pollutants in Nanjing City were investigated on the basis of data from nine national monitoring sites. These monitoring sites provide 24 hr average data to evaluate the spatiotemporal variations of $PM_{2.5}$ mass concentration. The characteristics of the annual, seasonal, monthly and hourly variations of $PM_{2.5}$ mass concentrations were analysed. $PM_{2.5}$ concentrations were higher in the winter months, yet lower in the summer and whole afternoon time, but became better and better during 2014-2016. Afterwards Pearson correlation coefficients were calculated between $PM_{2.5}$ and other criteria pollutants. The correlation coefficients between $PM_{2.5}$ and PM_{10} at 9 monitoring sites were more than or equal to 0.76, and were lower in spring while higher in winter, summer and fall. However, the correlation between $PM_{2.5}$ and SO_2, NO_2, CO varied in four seasons with lower correlation in summer and higher correlation in winter, spring and fall. Through calculating hourly correlation coefficients between $PM_{2.5}$ and PM_{10}, SO_2, NO_2, the correlation coefficients between $PM_{2.5}$ and PM_{10} were lower in the afternoon, on the contrary, the correlations of $PM_{2.5}$ and SO_2, NO_2 were lower in the night-time and morning. The correlation curves of $PM_{2.5}$ and O_3 barely changed, which gives us the information that O_3 was weakly correlated with $PM_{2.5}$. The investigation of $PM_{2.5}$ and other criteria pollutants may provide some implications for the key reasons leading to the regional high $PM_{2.5}$ and lay the foundation for further research of $PM_{2.5}$ control strategies in Nanjing.

INTRODUCTION

China's rapid economic development is one of the major factors of air pollution. $PM_{2.5}$ (particulate matter less than or equal to 2.5 μm) is an important part of air pollution and affects people's health. In the 1990s, some scholars had already studied the relationship between air pollutants and morbidity. Vedal et al. (1997) researched the associations between particles and several health outcomes in many settings and at vastly different particle concentrations. In this century, more and more scholars studied the relationship between $PM_{2.5}$ and health (Berglen 2004, Bell et al. 2007, Franklin et al. 2007, Ito et al. 2007, Chen et al. 2016).

In recent years, because the haze weather becoming more and more serious, Chinese government began to pay attention to the problem of the air quality. National Standard GB 3095-2012 for air quality was published in 2012, and nine monitoring sites were built in Nanjing City, which is located in the eastern China and belongs to Jiangsu Province with latitude ranging from 31°142'N to 32°372'N, and longitude ranging from 118°223' E to 119°143'E. At present, the study of Nanjing air pollution was a rough research on the urban level of the whole country based on national monitoring stations (Zhang et al. 2015, Fang et al. 2016, Xu et al. 2017). Also, many scholars studied chemical composition in a small area of the city (Wang et al. 2002, Yang et al. 2005, Hu et al. 2012, Shen et al. 2014). However, the analysis of $PM_{2.5}$ and other criteria pollutants' individual spatiotemporal characteristics were not straightforward. Therefore, this study investigated spatiotemporal variations of $PM_{2.5}$ and Pearson correlation coefficients between $PM_{2.5}$ and other criteria pollutants in Nanjing. The results may provide some implications for the key reasons leading to the regional high $PM_{2.5}$ and lay the foundation for further research of $PM_{2.5}$ control strategies in Nanjing.

MATERIALS AND METHODS

The concentration monitoring sites of PM2.5 and other criteria pollutants in Nanjing City: Nanjing city is the capital of Jiangsu Province, and nine national criteria pollutants monitoring sites were built in Nanjing. These sites collected criteria pollutants data every hour, including $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3. Fig. 1 shows the spatial distribution of the nine sites in Nanjing city. These sites were built in the main city zone, which does not include Luhe District, Jiangning District, Lishui District and Gaochun District.

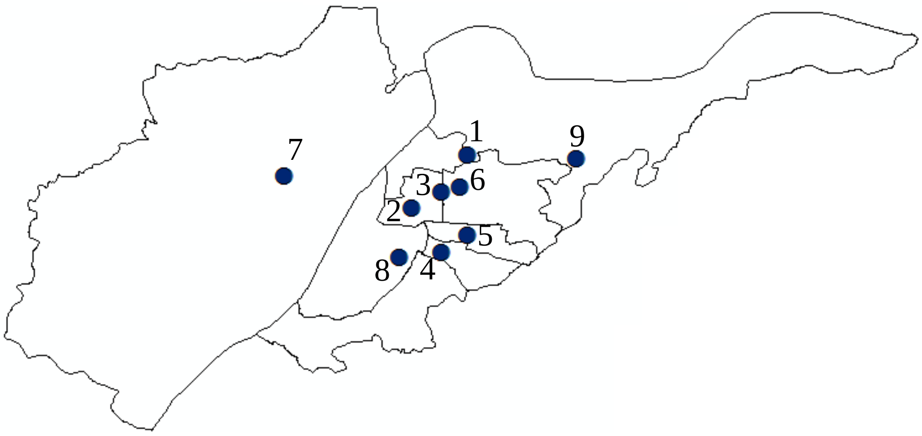

Fig. 1: $PM_{2.5}$ and other criteria pollutants concentration monitoring stations in Nanjing City.

Data acquisition: The monitoring data of $PM_{2.5}$ and other criteria pollutants concentration for the nine monitoring sites were extracted from Qingyue Open Environmental Data Center, which disposed the data from the publishing website of China National Environmental Monitoring Center (http://113.108.142.147:20035/emcpublish/). The data of each site were recorded once per hour, and was downloaded monthly from 2014 to 2016.

Data analysis: To quantify hourly variations, dataset was grouped into 24 hours from 2014 to 2016, and also to quantify seasonal variations, dataset was grouped into four seasons with winter in December, January and February; spring in March, April and May; summer in June, July and August; and fall in September, October and November. All the statistical tests were conducted using MATLAB software. In order to visually illustrate spatial variations, maps reporting $PM_{2.5}$ monitoring stations and associated $PM_{2.5}$ concentrations over time were developed using ArcMap 10.4.1.

RESULTS AND DISCUSSION

Spatiotemporal variations of PM2.5 concentration in Nanjing City: In order to detect the spatiotemporal variations of $PM_{2.5}$ concentration, the data were collected at nine sites in Nanjing City from 2014 to 2016. Fig. 2 shows the annual average $PM_{2.5}$ concentrations analysed in ArcMap at each site for 2014, 2015 and 2016.

From Fig. 2, the annual average $PM_{2.5}$ concentrations of all these nine sites exceeded 70 in 2014. It indicates that all these annual average $PM_{2.5}$ concentrations were more than doubled Chinese Ambient Air Quality Standards (CAAQS) Grade II standards (35 $\mu g/m^3$). In 2015, the average concentrations of the nine sites were between 50 $\mu g/m^3$ and 70 $\mu g/m^3$, and the values were all below 60 $\mu g/m^3$ in 2016. The best value was the concentration of Xianlindaxuecheng Site in 2016, which was 39.78 $\mu g/m^3$. It gives us information that the air quality was becoming better and better, but no concentration value was lower than CAAQS Grade II standards.

Temporal variations of monthly average $PM_{2.5}$ concentrations at nine sites: To further investigate the trend of $PM_{2.5}$ concentrations in Nanjing, monthly average $PM_{2.5}$ concentrations were analysed. Nine different colour lines represent the value of nine sites. Results at nine sites are shown in Fig. 3.

The obvious results can be found from Fig. 3 that the value of each site reached the minimum in August of 2014 and 2016, and in September of 2015, whereas the higher value appeared in the winter months. The values of nine sites were on the decline from winter to summer, and then on the rise from fall to winter.

Temporal variations of seasonal and hourly average $PM_{2.5}$ concentrations in 2014-2016: The hourly average $PM_{2.5}$ concentrations can be used to find daily patterns of exposure, and provide a reference for further effects of temperature and human activity on $PM_{2.5}$ mass. Therefore, dataset was grouped into 24 hours with four seasons in 2014, 2015 and 2015 respectively. In order to see the trend clearly, 24-hr concentration rose diagrams were plotted in OriginPro 9.1.

From Fig. 4, air quality was getting better and better, especially in summer and fall from 2014 to 2016. $PM_{2.5}$ concentration was better in summer than other seasons in every year, while it had the highest value in winter of each year. When it comes to hourly concentration, an obvious phenomenon is that the values from 1 pm to 8 pm were lower than

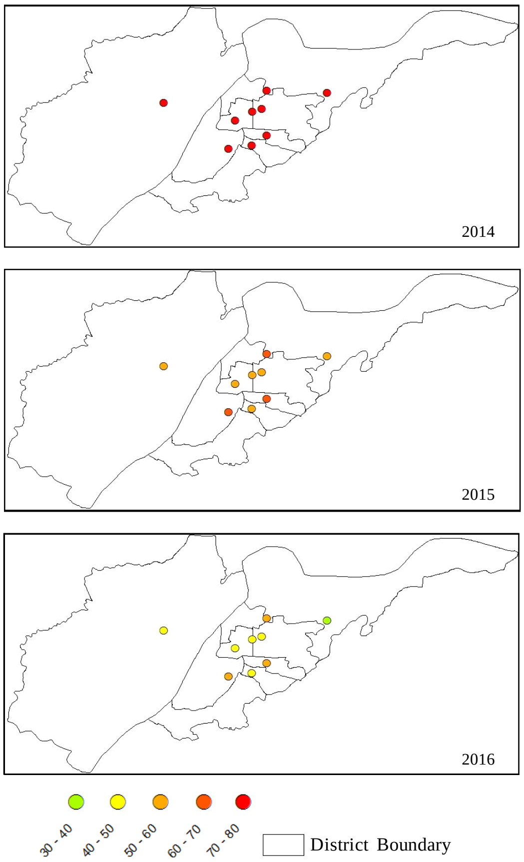

Fig. 2: Spatiotemporal variations of annual average $PM_{2.5}$ concentrations (μg/m^3) in Nanjing.

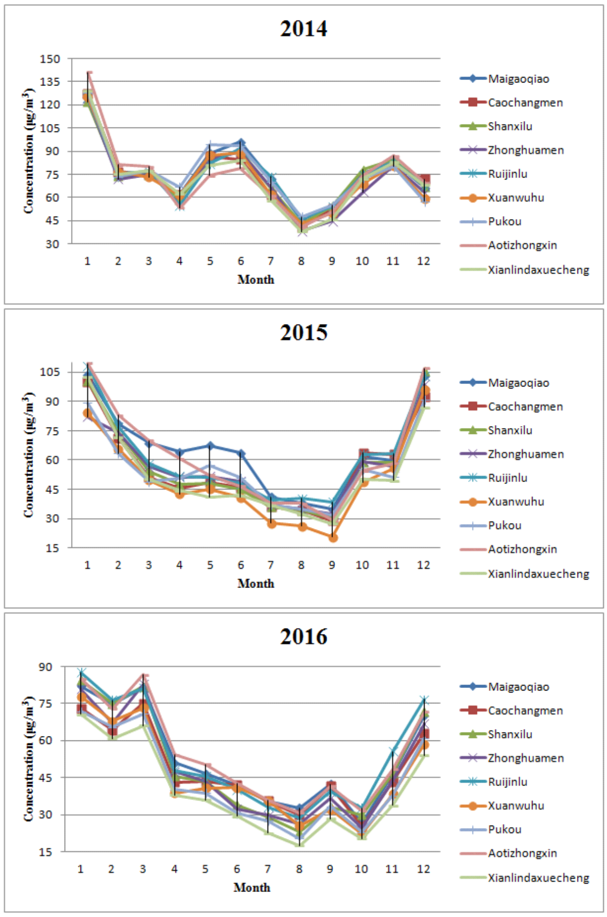

Fig. 3: Temporal variations of monthly average $PM_{2.5}$ concentrations at nine sites.

other times in all the seasons, and this period had the highest temperature during the whole day, which could be explained that $PM_{2.5}$ concentration is related to temperature.

Correlations between $PM_{2.5}$ and and other criteria pollutants concentrations: In order to better understand the contribution of other criteria pollutants to the total $PM_{2.5}$ mass, Spearman correlation coefficient was adopted, and the correlations between $PM_{2.5}$ and other criteria pollutants were analysed. The analyses also include seasonal and hourly correlations to account for the impact of ambient conditions. Table 1 shows the correlation between seasonal average $PM_{2.5}$ concentrations with other criteria pollutants at nine sites.

Pearson correlation coefficients were divided into strong correlation (0.60-1.00), moderate correlation (0.25-0.59) and weak correlation (less than 0.25). As it can be seen from Table 1, correlation coefficients between $PM_{2.5}$ and PM_{10} at nine monitoring sites were more than or equal to 0.76. From the averages of these 9 stations, the value was 0.79 in spring, while it was the same (0.91) in winter, summer and fall. It indicates that $PM_{2.5}$ was strongly correlated with PM_{10}, especially in winter, summer and fall. The correlation between $PM_{2.5}$ and SO_2, NO_2 and CO varied in four seasons with moderate correlation in summer and higher correlation in winter, spring and fall. However, the correlation coefficients between $PM_{2.5}$ and O_3 were all less than 0.25, especially less than 0 in the winter, spring and fall, which gives us the information that O_3 was weakly correlated with $PM_{2.5}$. It could be because O_3 is related to secondary $PM_{2.5}$, but not primary $PM_{2.5}$. This was also demonstrated by some scholars (Xie et al. 2015, Jia et al. 2017).

To further investigate the correlation between $PM_{2.5}$ and other criteria pollutants in Nanjing City, correlation coefficients between hourly average $PM_{2.5}$ concentrations and other criteria pollutants concentrations were also analysed. Because O_3 was weakly correlated with $PM_{2.5}$, correlation coefficients did not calculate O_3. Results of $PM_{2.5}$ with PM_{10}, SO_2, NO_2 and CO at nine sites are shown in Fig. 5.

From Fig. 5, correlation coefficients between $PM_{2.5}$ and PM_{10}, SO_2, NO_2 varied in 24 hours. The correlation coeffi-

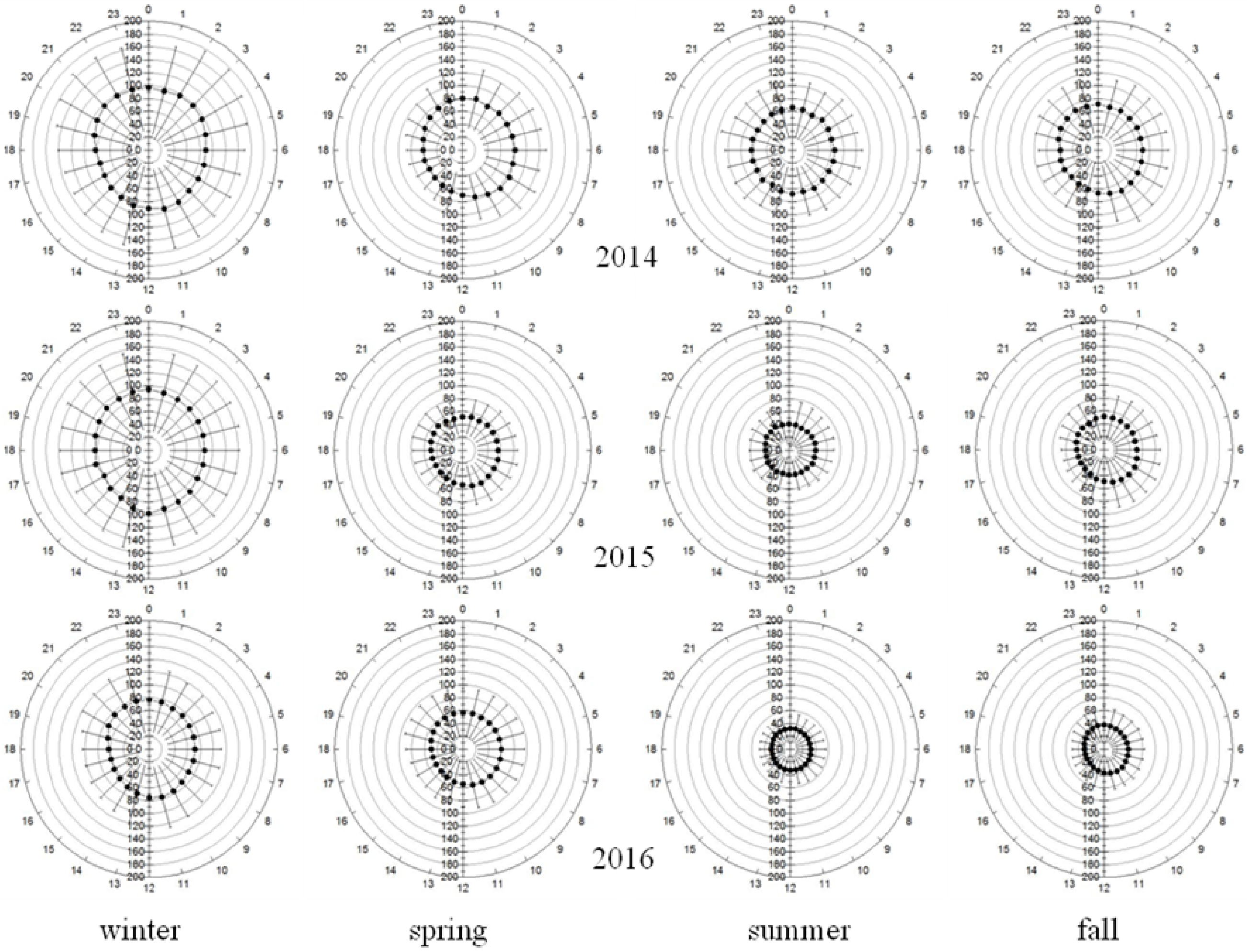

Fig. 4: Temporal variations of hourly average $PM_{2.5}$ concentrations in Nanjing City.

cients between $PM_{2.5}$ and PM_{10} were lower in the afternoon, while that between $PM_{2.5}$ and SO_2, NO_2 were lower in the night-time and morning. Some scholars suggested that SO_2 and NO_2 were secondary $PM_{2.5}$ source (Guerra et al. 2014), so this can demonstrate that temperature is one of the major factors to promote secondary composition. Except temperature, other factors can also affect it (Fu et al. 2016). The coefficients between $PM_{2.5}$ and CO had no obvious change, so it suggests that $PM_{2.5}$ and CO just had the same emission source, and the correlations were seldom influenced by external factors. This result will require further study.

CONCLUSION

In the past three years, Nanjing City exhibited higher $PM_{2.5}$ concentrations, and $PM_{2.5}$ concentrations demonstrated a strongly spatiotemporal variations at national monitoring sites. However, from the annual average values, $PM_{2.5}$ mass concentrations show significant reduction trend in Nanjing from 2014 to 2016. Monthly variations revealed that $PM_{2.5}$ concentrations were the most lowest in August or September and higher in winter months. The air quality was becoming better and better, but no concentration value of $PM_{2.5}$ was lower than CAAQS Grade II standards, so the government should take further measures to control the air quality. Pearson Correlation coefficients between seasonal average $PM_{2.5}$ concentrations and other criteria pollutants concentrations were analysed at nine sites. The result shows that the correlations between $PM_{2.5}$ and SO_2, NO_2 and CO mass concentrations varied in four seasons with higher correlation in winter and

Table 1: Correlation between seasonal average $PM_{2.5}$ concentrations with other criteria pollutants at nine sites.

	Site Name	Winter	Spring	Summer	Fall
$PM_{2.5}$ & PM_{10}	Maigaoqiao	0.91	0.80	0.93	0.91
	Caochangmen	0.93	0.81	0.93	0.91
	Shanxilu	0.91	0.76	0.90	0.91
	Zhonghuamen	0.89	0.79	0.93	0.92
	Ruijinlu	0.91	0.80	0.87	0.85
	Xuanwuhu	0.92	0.81	0.94	0.91
	Pukou	0.92	0.78	0.89	0.92
	Aotizhongxin	0.90	0.77	0.92	0.90
	Xianlindaxuecheng	0.91	0.78	0.90	0.92
	Average	**0.91**	**0.79**	**0.91**	**0.91**
$PM_{2.5}$ & SO_2	Maigaoqiao	0.46	0.36	0.21	0.45
	Caochangmen	0.47	0.30	0.29	0.56
	Shanxilu	0.49	0.41	0.33	0.51
	Zhonghuamen	0.46	0.41	0.27	0.56
	Ruijinlu	0.48	0.39	0.42	0.53
	Xuanwuhu	0.49	0.36	0.32	0.45
	Pukou	0.51	0.39	0.03	0.50
	Aotizhongxin	0.38	0.30	0.06	0.18
	Xianlindaxuecheng	0.51	0.47	0.30	0.48
	Average	**0.47**	**0.38**	**0.25**	**0.47**
$PM_{2.5}$ & NO_2	Maigaoqiao	0.38	0.39	0.39	0.36
	Caochangmen	0.48	0.49	0.34	0.53
	Shanxilu	0.42	0.44	0.34	0.39
	Zhonghuamen	0.47	0.47	0.40	0.46
	Ruijinlu	0.51	0.48	0.40	0.51
	Xuanwuhu	0.41	0.36	0.30	0.28
	Pukou	0.38	0.36	0.37	0.44
	Aotizhongxin	0.38	0.36	0.15	0.30
	Xianlindaxuecheng	0.37	0.37	0.10	0.31
	Average	**0.42**	**0.41**	**0.31**	**0.40**
$PM_{2.5}$ & CO	Maigaoqiao	0.53	0.26	0.27	0.38
	Caochangmen	0.67	0.56	0.33	0.43
	Shanxilu	0.50	0.53	0.38	0.35
	Zhonghuamen	0.60	0.45	0.11	0.47
	Ruijinlu	0.66	0.60	0.31	0.50
	Xuanwuhu	0.67	0.49	0.37	0.52
	Pukou	0.52	0.19	0.40	0.30
	Aotizhongxin	0.37	0.18	0.21	0.55
	Xianlindaxuecheng	0.74	0.53	0.49	0.57
	Average	**0.58**	**0.42**	**0.32**	**0.45**
$PM_{2.5}$ & O_3	Maigaoqiao	-0.15	-0.16	0.16	-0.05
	Caochangmen	-0.19	-0.09	0.21	-0.02
	Shanxilu	-0.17	-0.15	0.14	-0.09
	Zhonghuamen	-0.20	-0.20	0.12	-0.08
	Ruijinlu	-0.22	-0.21	-0.02	-0.15
	Xuanwuhu	-0.17	-0.10	0.10	-0.10
	Pukou	-0.18	-0.09	0.13	-0.02
	Aotizhongxin	-0.08	-0.19	0.17	-0.11
	Xianlindaxuecheng	-0.16	-0.12	0.17	-0.06
	Average	**-0.17**	**-0.15**	**0.13**	**-0.08**

lower correlation in summer, spring and fall, while correlations between $PM_{2.5}$ and PM_{10} were lower in spring and higher in winter, summer and fall. The correlations between $PM_{2.5}$ and PM_{10}, SO_2, NO_2 also varied in 24 hours, which indicates that $PM_{2.5}$ and these three criteria pollutants had immanent relation. In the meantime, this relationship was affected by other factors. Therefore, $PM_{2.5}$ in Nanjing is generated by multiple sources, with great variations among different areas and different seasons. Future studies should investigate $PM_{2.5}$ chemical component, so that the relationship between $PM_{2.5}$ and other criteria pollutant variations of emissions in different regions will be discovered.

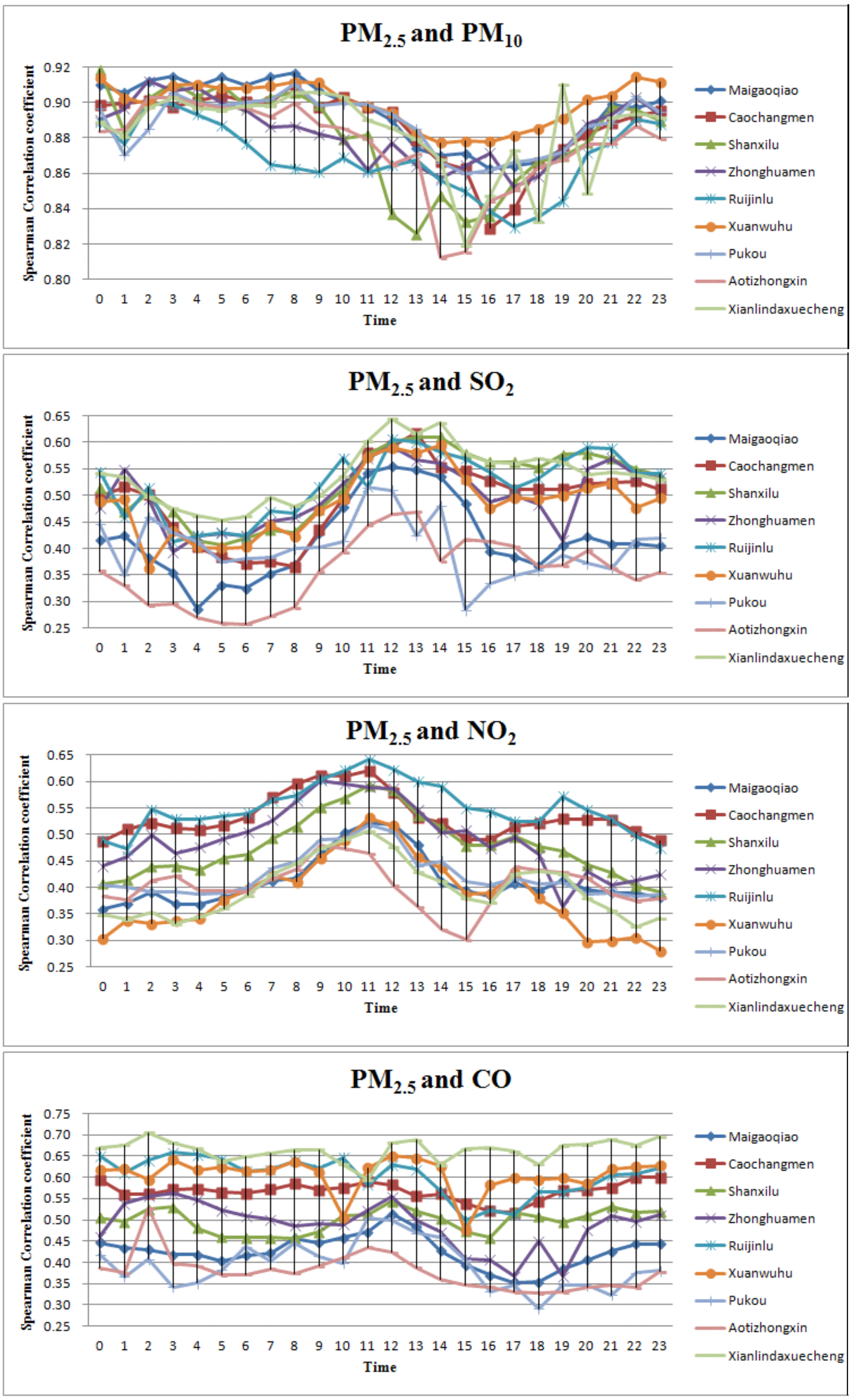

Fig. 5: Correlation of hourly average $PM_{2.5}$ concentrations with other criteria pollutants in Nanjing City at nine sites.

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