Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268 e-ISSN: 2395-3454	Vol. 17	No. 4	pp. 1105-1113	2018

Original Research Paper | Open Access

Comparison of Spatiotemporal Variations and Pearson Correlation Coefficients of $PM_{2.5}$ Between Jiangsu Province and the State of North Carolina

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 17-03-2018
Accepted: 04-06-2018

Key Words:
Spatiotemporal variations
Pearson correlation coefficient
$PM_{2.5}$ mass concentration
Jiangsu Province
North Carolina

ABSTRACT

Fine particulate matter ($PM_{2.5}$) is an important air pollutant, which can lead to visibility degradation and adverse health effects. In recent years, heavy and large-scale haze has been a serious issue caused by regional high $PM_{2.5}$ concentrations in China. On the contrary, the most areas of United States have been $PM_{2.5}$ attainment regions due to well-established air pollution control strategies. The comparison of $PM_{2.5}$ mass concentrations, both in China and United States, can provide good evaluation regarding the seriousness of air pollution in China. This research aimed to compare the $PM_{2.5}$ pollution, both in Jiangsu Province of China and the State of North Carolina of United States, to evaluate the spatiotemporal variations of $PM_{2.5}$. The 13 $PM_{2.5}$ concentration monitoring prefecture-level cities in Jiangsu Province and 11 $PM_{2.5}$ concentration monitoring cities in North Carolina have good quality data, and provide the 24-hr average data to evaluate the spatial and temporal variations of $PM_{2.5}$ mass concentration in both the regions. Furthermore, Pearson correlation coefficient was introduced to investigate the relationship between each pair of cities, and the results show that Pearson correlation coefficients were proportional to the distance in Jiangsu. However, there was no strong correlation between the cities in North Carolina. The comparison of $PM_{2.5}$ in Jiangsu and North Carolina may provide some implications for the key reasons leading to the regional high $PM_{2.5}$ and the establishment of effective $PM_{2.5}$ control strategies in China.

INTRODUCTION

Particulate matter (PM) with aerodynamic equivalent diameter (AED) less than or equal to 2.5 μm ($PM_{2.5}$) is an important air pollutant, which can cause haze problem and has potential risks to human health. In recent years, the $PM_{2.5}$ pollution has been a severe environmental problem and gained intensive attention in China. Wang et al. (2003) revealed that the acidity of $PM_{2.5}$ in Nanjing city was stronger than that of PM_{10}. Ito et al. (2007) studied the characterization of $PM_{2.5}$ and air pollution and weather variables in the context of health effect models. Bell et al. (2007) identified spatiotemporal variation in $PM_{2.5}$ chemical composition in the United States for health effects. On the contrary, the air quality in the United States is generally good due to well established air pollution control strategies. Numerous researches have been performed to investigate the concentration variation of $PM_{2.5}$ in China and the United States.

There were many scholars studying $PM_{2.5}$ in the United States in the last century (Cahill et al. 1981, Malm 1994, Parkhurst et al. 1999). In the first ten years of the twenty-first century, some Chinese scholars had begun to study $PM_{2.5}$. Ye et al. (2003) collected weekly $PM_{2.5}$ samples at two sites to measure $PM_{2.5}$ concentrations in Shanghai for 1 year. Weekly $PM_{2.5}$ mass concentrations ranged from 21 to 147 μg/m^3, with annual average concentrations of 57.9 μg/m^3 and 61.4 μg/m^3 at two sites. Seasonal variation of $PM_{2.5}$ concentrations was significant, with the highest concentrations observed from mid-November through December and the lowest from June through September.

Zheng et al. (2005) researched the seasonal trends in $PM_{2.5}$ source contributions in Beijing. The 24-hr $PM_{2.5}$ samples were taken at 6-day intervals at five urban and rural sites simultaneously for 1 month in each quarter of the calendar year 2000.

Yang et al. (2005) collected the $PM_{2.5}$ samples at an urban and a suburban site in Nanjing. They were analysed for inorganic ions, elemental carbon, organic carbon (OC), water-soluble organic carbon (WSOC), and individual WSOC and nonpolar organic species. Coal combustion, vehicular emissions, secondary inorganic and organic aerosols, and road/sea salt were the major contributing sources to the identified $PM_{2.5}$ aerosol mass.

In 2012, the Chinese government had begun to attach importance to air pollution and promulgated ambient air quality standards (National Standard GB 3095-2012). Beijing Municipal Environmental Protection Monitoring Center (BMEMC) published $PM_{2.5}$ research monitoring hourly concentration data in real time on January 21st, 2012. There were 68 state-controlled automatic air quality monitoring stations in Jiangsu Province and published monitoring results in real-time.

Many Chinese scholars used these data to analyse the characteristics of $PM_{2.5}$. Chai et al. (2014) studied the data of $PM_{2.5}$ in 15 cities, and accounted for a large proportion of airborne particles, the concentrations of $PM_{2.5}$ were much higher than the values recommended by the World Health Organization. Fang et al. (2016) investigated the spatiotemporal variations of $PM_{2.5}$ concentrations in China based on observed data from 945 automatic air quality monitoring sites across China in 2014.

In China, $PM_{2.5}$ monitoring sites were always placed in the cities, so the research was mainly performed in megacities. In recent years, more and more research has been done in this field. He et al. (2012) investigated the spatial and seasonal variations in $PM_{2.5}$ acidity in two megacities, Beijing and Chongqing, in order to discern the formation of secondary inorganic aerosols. Xie et al. (2015) analysed the variations of mass concentrations of $PM_{2.5}$ in 31 Chinese provincial capital cities, and used the Pearson correlation coefficient to establish the relationship between $PM_{2.5}$ and other criteria pollutants, including PM_{10}, SO_2, NO_2, CO and O_3. Xu et al. (2017) analysed $PM_{2.5}$ concentrations in 23 cities, and got spatial and temporal trends and quantified the regional component of $PM_{2.5}$ pollution.

In the United States, some scholars also focused on megacities. Maykut et al. (2003) used the multivariate receptor models Positive Matrix Factorization (PMF) and Unmix with the EPA's Chemical Mass Balance model to deduce the sources of $PM_{2.5}$ at a centrally located urban site in Seattle. Butler et al. (2003) established a monitoring network to measure $PM_{2.5}$ for one year in metropolitan Atlanta, Georgia. Ito et al. (2007) compiled daily data for $PM_{2.5}$ and other criteria pollutants, some weather factors for New York City from 1999 to 2002, and analysed the spatiotemporal variation of $PM_{2.5}$ and measured gaseous pollutants at multiple monitors.

Through the above illustration, there have been a lot of research in the $PM_{2.5}$ field, but there was no scholar study on the comparison of $PM_{2.5}$ concentrations in China and United States, and this study can provide good evaluation regarding the seriousness of air pollution in China. In this study, the variations of mass concentrations of $PM_{2.5}$ were investigated based on the data of 11 sites in North Carolina State and 13 prefecture-level cities in Jiangsu Province from 2014 to 2016. By comparing $PM_{2.5}$ concentrations over this length of time, the characteristics of the monthly and seasonal variations of mass concentrations of air pollutants were determined. Consequently, the purpose of this research is to quantitatively characterize the concentration of $PM_{2.5}$ in spatial and temporal scales in Jiangsu Province and the State of North Carolina, and comparison of these data may provide some implications for the key reasons leading to the regional high $PM_{2.5}$ and the establishment of effective $PM_{2.5}$ control strategies in China.

MATERIALS AND METHODS

$PM_{2.5}$ monitoring stations in the State of North Carolina: This research selected Jiangsu Province and the State of North Carolina for investigation. Jiangsu Province is in eastern China bordering the East China Sea to the east, with latitude ranging from 30°45' N to 35°20' N, while North Carolina State is in the southeastern U.S. bordering Atlantic Sea to the east, with latitude ranging from 33°50' N to 36°35' N.

In North Carolina, $PM_{2.5}$ mass concentrations were routinely monitored at more than twenty cities and Local Air Monitoring Stations (SLAMS) and related ambient air monitoring networks (https://www3.epa.gov/ttnamti1/slams.html. Accessed on March 18, 2016). After researching the data from 2014 to 2016, selected 11 sites had relatively good quality data, and these $PM_{2.5}$ mass concentration monitoring cities were evenly distributed across the whole State. Fig. 1 shows the spatial distribution of these 11 monitoring cities in the State of North Carolina. Under the SLAMS, $PM_{2.5}$ concentration measurements were taken once every day using either Federal Reference Method (FRM) or Federal Equivalent Method (FEM).

$PM_{2.5}$ monitoring stations in Jiangsu Province: In China, Jiangsu Province had the second largest absolute GDP in the past 3 years (2014-2016), so every prefecture-level city had several $PM_{2.5}$ monitoring points. Analysis of $PM_{2.5}$ spatiotemporal variations started with the identification of national $PM_{2.5}$ monitoring stations in Jiangsu and obtaining $PM_{2.5}$ data for each given station. Under the National Air Monitoring Stations for criteria pollutants, $PM_{2.5}$ mass concentrations were also routinely monitored at 13 prefecture-level cities. But Jiangsu Province does not have stations monitored and analysed $PM_{2.5}$ chemical component, so the comparison was just applied in the concentration. Fig. 2 shows the spatial distribution of 13 prefecture-level cities in Jiangsu Province.

Data acquisition and processing: The pre-generated data of $PM_{2.5}$ concentrations for the 11 monitoring cities of North

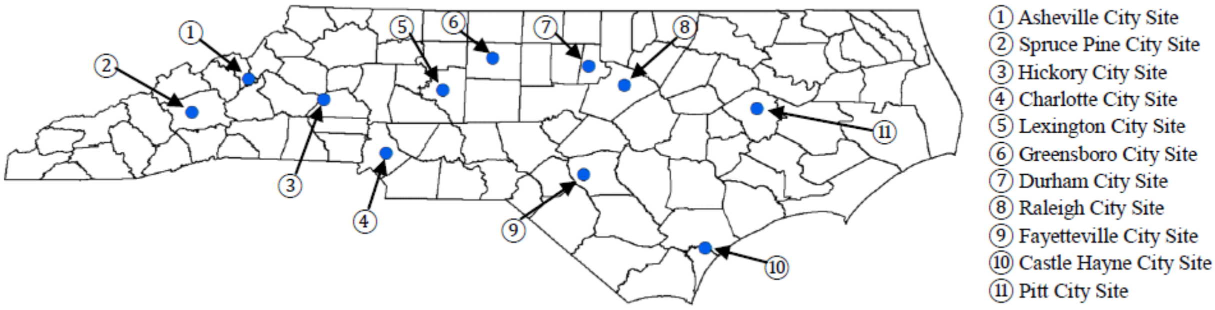

Fig. 1: $PM_{2.5}$ mass measurement stations in North Carolina of USA.

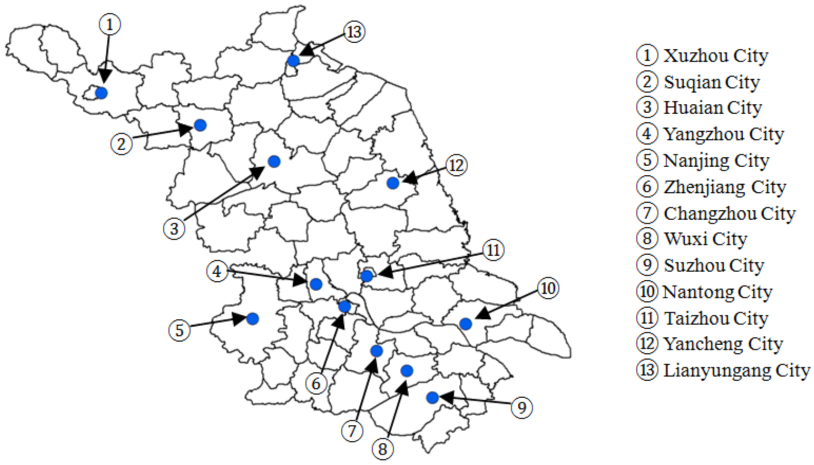

Fig. 2: $PM_{2.5}$ mass measurement stations in Jiangsu Province of China.

Carolina were extracted from EPA's website in the past three years (2014-2016), but because of several months data not released, eight monitoring sites had 9 months data in 2016, and Charlotte City site had 11 months data in 2016, and Durham City site and Pitt Agricultural Center site had first 6 months data in 2016. The monitoring data of $PM_{2.5}$ concentrations for the 13 monitoring cities of Jiangsu were extracted from Qingyue Open Environmental Data Center.

The values N/A of $PM_{2.5}$ mass concentration were deleted, the number of the remaining data point was not remarkably reduced. All the statistical tests were performed using MATLAB software. To visually illustrate spatial variations, maps reporting $PM_{2.5}$ monitoring stations and associated $PM_{2.5}$ concentrations over time were developed using ArcGIS.

Pearson correlation coefficient: To further compare $PM_{2.5}$ mass concentration between Jiangsu and North Carolina, Pearson correlation coefficient was introduced to the investigation. Pearson correlation coefficient was put forward by Galton in the late 19th century. The equation is given as follows (Adler et al. 2010).

$$R = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad ...(1)$$

Where, R is the correlation coefficient ranging from -1 to 1, n is the number of samples, X_i and Y_i represent the data of the two variables monitored on Day I, and $\bar{X}$ and $\bar{Y}$ represent the mean of variables, respectively.

RESULTS AND DISCUSSION

Spatial and temporal variations of $PM_{2.5}$ concentration in North Carolina: The $PM_{2.5}$ concentrations were monitored at selected 11 cities in the State of North Carolina from 2014 to 2016 to detect the spatial and temporal variations. For the purpose of illustration, Fig. 3 shows the annual average $PM_{2.5}$ concentrations at each site for 2014, 2015 and 2016, and these sites can represent different regions.

In general, the annual average $PM_{2.5}$ concentrations were pretty good from 2014 to 2016, and better than the con-

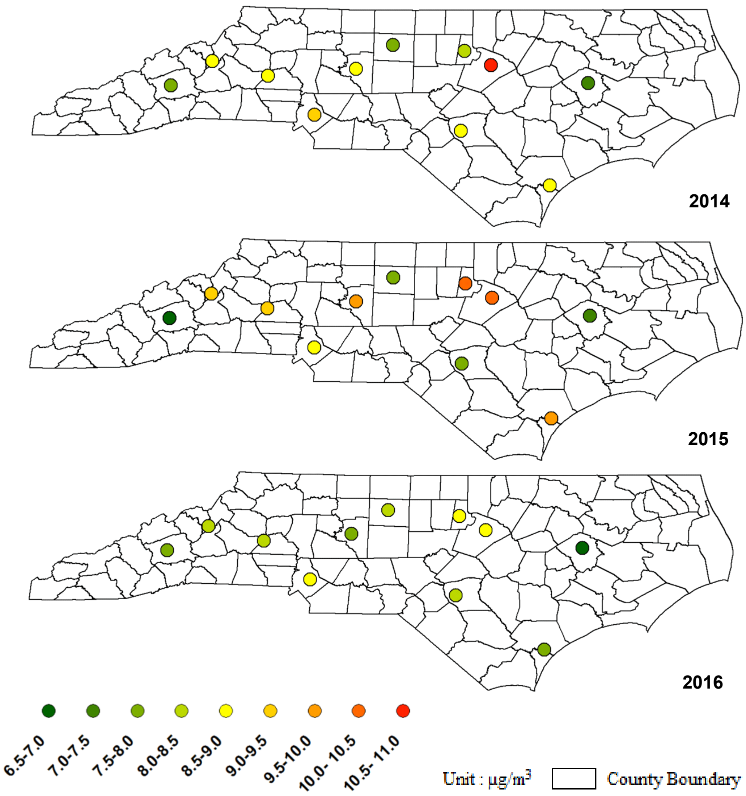

Fig. 3: Spatial and temporal variations of annual average $PM_{2.5}$ concentrations (µg/m³) in NC.

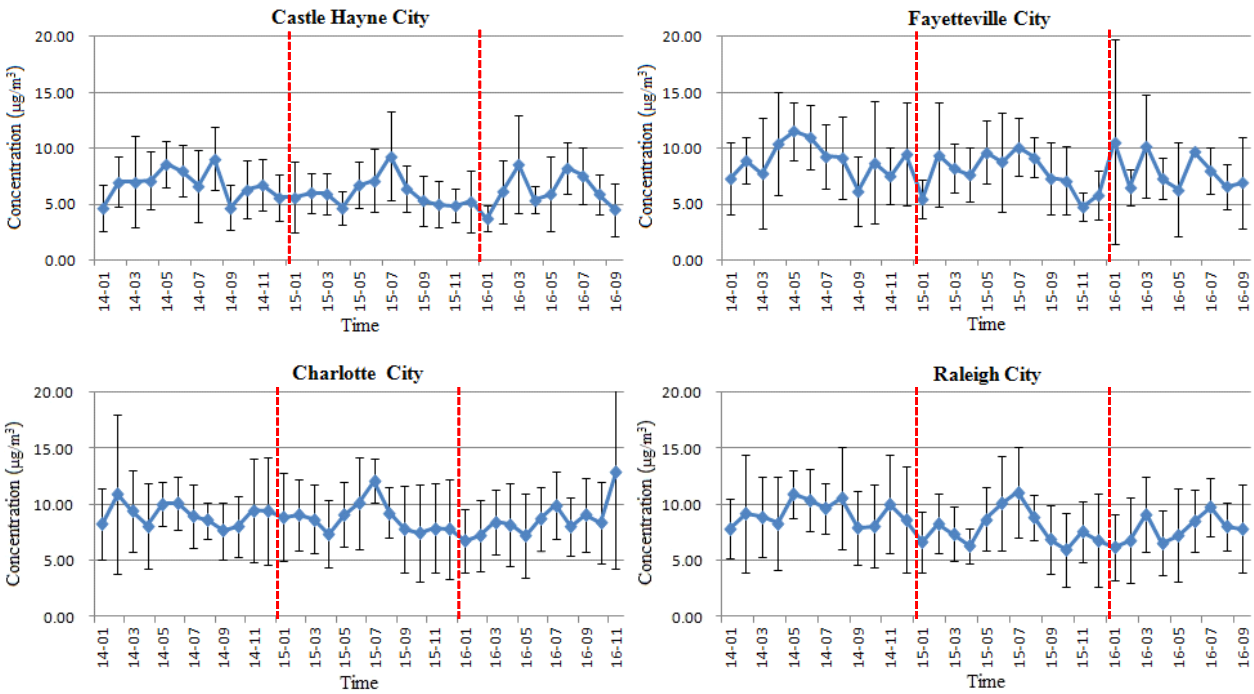

Fig. 4: Temporal variations of monthly average $PM_{2.5}$ concentrations at four representative cities in NC.

Table 1: Seasonal variations of $PM_{2.5}$ concentrations (μg/m³) in 11 monitoring sites of NC.

Sites	Winter	Spring	Summer	Fall
Castle Hayne City	5.53±2.42	6.69±2.95	7.66±2.86	5.45±2.21
Fayetteville City	8.02±4.69	8.83±3.67	9.06±2.84	6.91±3.24
Charlotte City	8.50±4.29	8.48±3.19	9.50±2.83	8.70±4.57
Raleigh City	7.53±3.72	8.03±3.24	9.59±3.07	7.72±3.56
Average	7.39±3.78	8.01±3.26	8.95±2.90	7.20±3.40

Table 2: Seasonal variations of $PM_{2.5}$ concentrations (μg/m³) in four representative cities.

Sites	Winter	Spring	Summer	Fall
Nanjing	82.05±47.93	59.86±32.06	46.86±32.25	49.64±33.00
Wuxi	81.80±43.24	60.68±26.62	41.36±22.16	48.94±26.84
Lianyungang	84.37±57.28	53.31±29.01	37.65±28.54	41.82±30.86
Xuzhou	101.46±56.11	61.21±27.41	47.87±25.39	52.15±32.52
Average	87.42±51.14	58.77±28.78	43.44±27.09	48.14±30.81

centrations from 2005 to 2013 (Cheng et al. 2016), although the annual average concentration threshold was strengthened from 15 μg/m³ to 12 μg/m³ in 2012 (NAAQS table, available at https://www.epa.gov/criteria-air-pollutants/naaqs-table. Accessed on March 18, 2016). From the Fig. 3, only Raleigh was close to 11 μg/m³ in 2014 and 2015, and Raleigh and Durham were close to 11 μg/m³ in 2014, while other areas exhibited lower annual average $PM_{2.5}$ concentrations. Specifically, lower $PM_{2.5}$ concentrations always occurred in east coastal plain areas. To further investigate the reduction trend of $PM_{2.5}$ concentrations in NC, higher resolution datasets, monthly average $PM_{2.5}$ concentrations, were analysed. Results at four representative cities are shown in Fig. 4.

The monthly average $PM_{2.5}$ concentrations at these 11 cities were found to have no significant differences from 2014 to 2016. In order to exhibit the characteristics, seasonal variations of $PM_{2.5}$ concentrations were observed from the above plots. Seasonal variations and trends were studied by a lot of American scholars (Kim 2002, Malm 1994, Russell 2004), and also by some Chinese scholars (Ye et al. 2003, Zheng et al. 2005). Huang et al. (2012) had studied this topic in Beijing, Shanghai. The seasonal variations of $PM_{2.5}$ mass concentration in this period are summarized in Table 1.

As can be seen from Table 1, in general, $PM_{2.5}$ concentrations were the highest in summer and the most lowest in fall at 11 monitoring sites, and there was no exception, but seasonal variations were not significantly different at all these cities in 2014-2016. The spatial variations of $PM_{2.5}$ concentrations in NC were consistent with the finding of Cheng (2016). The spatial pattern of $PM_{2.5}$ concentrations can be attributed to the spatial heterogeneity of emission sources. This may be due to the aforementioned implementation of Cross-State Air Pollution Rule in 2012, effective emission control on NO_2 and SO_2 that contribute to chemical components of secondary $PM_{2.5}$ continued in USA (Guerra et al. 2014).

Spatial and temporal variations of $PM_{2.5}$ concentration in Jiangsu: The $PM_{2.5}$ concentrations were monitored at 13 cities in Jiangsu Province from 2014 to 2016 to detect the spatiotemporal variations. Just like the illustration in North Carolina, Fig. 5 shows the annual average $PM_{2.5}$ concentrations at each site for 2014, 2015 and 2016. The annual average $PM_{2.5}$ concentrations were higher than the concentrations in North Carolina. Specifically, the cities in northwest Jiangsu such as Xuzhou and Suqian exhibited higher $PM_{2.5}$ concentrations for the past three years, while lower $PM_{2.5}$ concentrations always occurred in east coastal plain areas. The concentrations in all these sites became better and better in last three years.

To further investigate the reduction trend of $PM_{2.5}$ concentrations in Jiangsu, monthly average $PM_{2.5}$ concentrations were also analysed. Results at four representative cities are shown in Fig. 6.

The monthly average $PM_{2.5}$ concentrations at the 13 cities exhibited reduction trend from 2014 to 2016 as well, and the value of each city reached the minimum in August or September of all the three years. In addition, a seasonal variation of $PM_{2.5}$ concentration can also be observed from the above plots. The seasonal variation of $PM_{2.5}$ mass concentrations in this period are summarized in Table 2.

As shown in Table 2, $PM_{2.5}$ concentrations were significantly higher in winter and lower in summer at four repre-

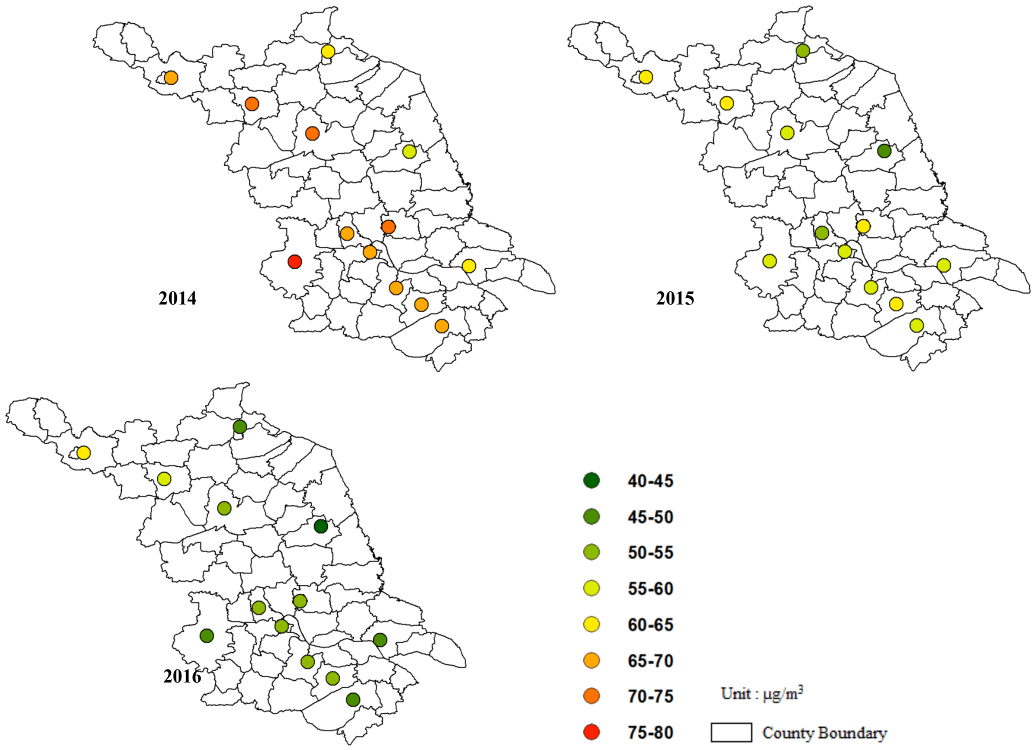

Fig. 5: Spatial and temporal variations of annual average $PM_{2.5}$ concentrations (μg/m^3) in Jiangsu.

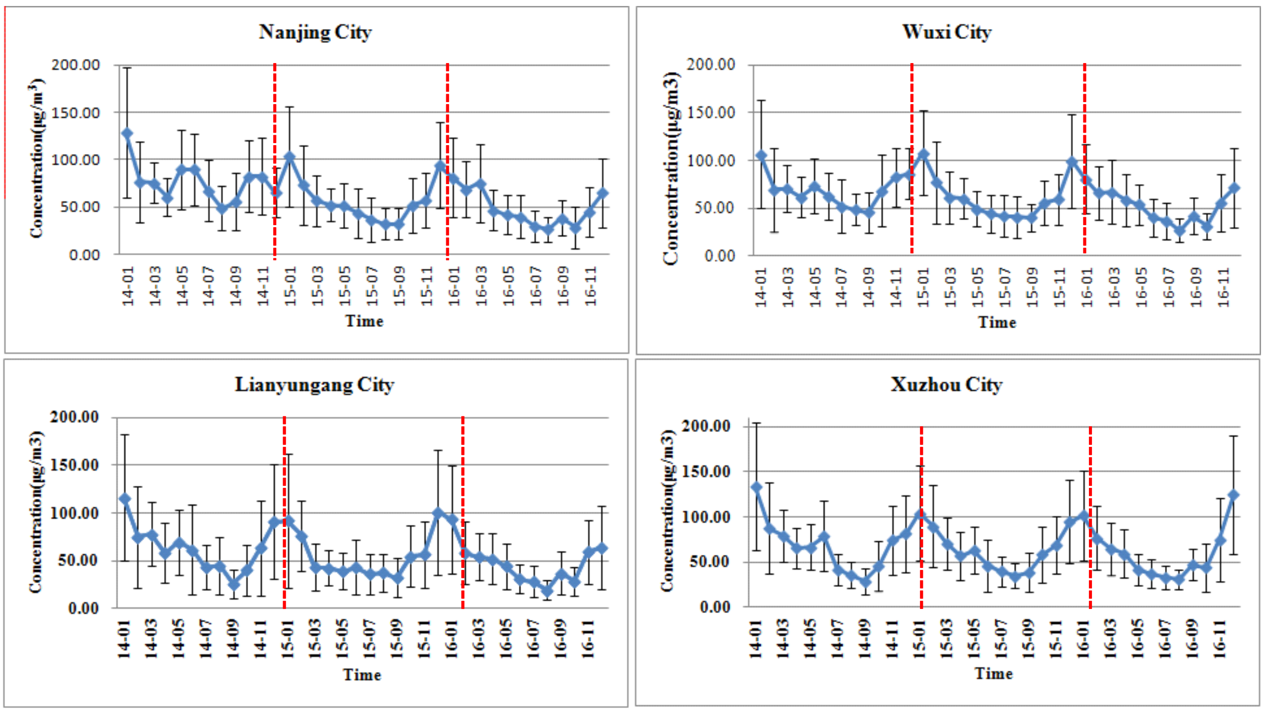

Fig. 6: Temporal variations of monthly average $PM_{2.5}$ concentrations (μg/m^3) at four representative cities in Jiangsu.

Fig. 7(a): A curve was made from the west to east of North Carolina, and a perpendicular line was given from Charlotte to the curve. Eight cities are close to this curve. (b) A curve was made from the northwest to southeast of Jiangsu Province, and a perpendicular line was given form Nanjing to the curve. Ten cities are close to this curve.

Table 3: Pearson correlation coefficients of annual average $PM_{2.5}$ concentrations among nine cities in North Caroline. The coefficient values between Charlotte and other eight cities are given in boldface.

	Spruce Pine	Asheville	Hickory	Charlotte	Lexington	Greensboro	Durham	Raleigh	Pitt
Spruce Pine	1	0.6374	0.4599	0.5440	0.0336	0.1590	-0.0206	0.7640	0.5257
Asheville	0.6374	1	0.6363	0.5675	-0.3180	0.3983	0.1030	0.5505	0.7231
Hickory	0.4599	0.6363	1	0.6819	-0.0340	0.6568	-0.0127	0.5902	0.6907
Charlotte	**0.5440**	**0.5675**	**0.6819**	**1**	**0.0267**	**0.3246**	**-0.2263**	**0.6772**	**0.7772**
Lexington	0.0336	-0.3180	-0.0340	0.0267	1	0.0665	0.4402	0.0498	-0.0319
Greensboro	0.1590	0.3983	0.6568	0.3246	0.0665	1	0.2214	0.1312	0.4582
Durham	-0.0206	0.1030	-0.0127	-0.2263	0.4402	0.2214	1	-0.2476	0.0354
Raleigh	0.7640	0.5505	0.5902	0.6772	0.0498	0.1312	-0.2476	1	0.642
Pitt	0.5257	0.7231	0.6907	0.7772	-0.0319	0.4582	0.0354	0.642	1

Table 4: Pearson correlation coefficients of annual average $PM_{2.5}$ concentrations among ten cities in Jiangsu Province. The coefficient values between Nanjing and other nine cities are given in boldface.

	Xuzhou	Suqian	Huaian	Taizhou	Yangzhou	Nanjing	Zhenjiang	Changzhou	Wuxi	Suzhou
Xuzhou	1	0.8493	0.8073	0.6911	0.7327	0.6847	0.7027	0.6959	0.6473	0.5950
Suqian	0.8493	1	0.9113	0.7859	0.7870	0.7179	0.7851	0.7475	0.6877	0.6491
Huaian	0.8073	0.9113	1	0.8558	0.8283	0.7602	0.8210	0.8105	0.7710	0.7253
Taizhou	0.6911	0.7859	0.8558	1	0.9092	0.8212	0.9157	0.8851	0.8247	0.7865
Yangzhou	0.7327	0.7870	0.8283	0.9092	1	0.8561	0.9252	0.8615	0.7895	0.7540
Nanjing	**0.6847**	**0.7179**	**0.7602**	**0.8212**	**0.8561**	**1**	**0.8872**	**0.8690**	**0.8337**	**0.7748**
Zhenjiang	0.7027	0.7851	0.8210	0.9157	0.9252	0.8872	1	0.9084	0.8453	0.7958
Changzhou	0.6959	0.7475	0.8105	0.8851	0.8615	0.8690	0.9084	1	0.9410	0.8990
Wuxi	0.6473	0.6877	0.7710	0.8247	0.7895	0.8337	0.8453	0.9410	1	0.9511
Suzhou	0.5950	0.6491	0.7253	0.7865	0.7540	0.7748	0.7958	0.8990	0.9511	1

sentative cities in 2014-2016. The average values in winter of these cities were about two times as large as the one in summer, and the average in fall was approximately ten percent higher than the one in summer.

Pearson correlation coefficients between each pair of cities in Jiangsu and North Carolina: Charlotte, which is the biggest city in North Carolina, was selected as the center of gravity. Then a curve was made from the west to east of North Carolina, and a perpendicular line was given from Charlotte to the curve. Fig. 7(a) shows that there are eight cities close to this curve. Pearson correlation coefficients of annual average $PM_{2.5}$ mass concentrations among Charlotte and other eight cities in North Carolina were calculated.

In Jiangsu Province, the biggest city, Nanjing, was also selected as the center of gravity. A curve from the northwest to southeast of Jiangsu Province was made, as it can be seen in Fig. 7(b), there are ten cities close to this curve, and a perpendicular line was given from Nanjing to the curve.

Table 3 shows Pearson correlation coefficients of annual average $PM_{2.5}$ concentrations among nine cities in North Carolina, especially coefficient values between Charlotte and other eight cities are given in boldface. Pearson correlation coefficients between Charlotte and the eight cities which are close the curve are shown in Fig. 7(a).

From Table 3, coefficients between Spruce Pine, Asheville, Hickory and Charlotte are strong or moderate correlations. These four cities belong to the west. However, the values of Pearson correlation coefficients showed no positive relationship among the cities of North Carolina, especially in the middle. The coefficient between Raleigh, and Pitt and Charlotte are 0.6772, 0.7772, which may be because these three cities have the similar emissions, and also because the concentration of $PM_{2.5}$ was low that can be easily affected by stochastic noise.

It can be seen from Table 4 that the correlations of $PM_{2.5}$ concentration between each pair of the cities in Jiangsu are very strong. Pearson correlation coefficient is proportional to the distance on the curve from Xuzhou to Suzhou with Nanjing as the center of gravity. The coefficient between Zhenjiang and Nanjing which has the nearest distance to Nanjing is 0.8872, and the coefficient between Xuzhou and Nanjing which has the farthest distance to Nanjing is 0.6847. From the whole Jiangsu situation, the coefficients between Xuzhou and Suzhou reached 0.5950, indicating that the whole Jiangsu has a strong $PM_{2.5}$ correlation.

CONCLUSION

During 2014-2016, lower $PM_{2.5}$ concentrations occurred in whole NC State, while Jiangsu exhibited higher $PM_{2.5}$ concentrations, and $PM_{2.5}$ mass concentration exhibited strong spatial and temporal variations at $PM_{2.5}$ monitoring sites in Jiangsu. Significant $PM_{2.5}$ mass reduction trend was observed in Jiangsu from 2014 to 2016. Seasonal variation analysis indicated that $PM_{2.5}$ concentrations were the lowest in summer and the highest in winter in Jiangsu Province, while that were the highest in summer and lowest in fall in North Carolina. It might have been due to the concentration of $PM_{2.5}$ in North Carolina was low, so it was not easy to spread, and the correlation among cities was not high. However, the concentration of $PM_{2.5}$ in Jiangsu was higher, so it was easy to spread, and the correlation coefficients between each pair of cities were higher. These can provide some insights to the holistic understanding of $PM_{2.5}$ on a regional scale. This study only analysed and compared the concentration between Jiangsu Province and the State of North Carolina, but it could effectively investigate the spatiotemporal characteristics. Future research should collect and analyse $PM_{2.5}$ chemical component data, so that the real source of $PM_{2.5}$ and the impact on the human body can be revealed.

ACKNOWLEDGEMENTS

This study was supported by the Fundamental Research Funds for the Central Universities of China (No. KYTZ201661), China Postdoctoral Science Foundation (No. 2015M571782), and Jiangsu Agricultural Machinery Foundation (No. GXZ14002). The authors gratefully acknowledge Qingyue Open Environmental Data Center for the provision of environmental data.

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