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ORIGINAL RESEARCH PAPER

Spatial and Temporal Analysis of Air Pollutants in Jiangsu Province, China

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ABSTRACT

Air pollution in China is a recurring issue and requires continuous attention and rigorous action. This research aims to study the standard air pollutants and air quality index in the Jiangsu province of China. The present study will complement the existing understanding on the distribution of six criteria air pollutants in different cities of Jiangsu province and its seasonal variation. Spatial analysis indicated Xuzhou city in the northern part of the province to have high average values of particulate matter ($PM_{2.5}$: 63.4 μg/m^3, PM_{10}: 115.4 μg/m^3), sulphur dioxide (30 μg/m^3), carbon monoxide (1.18 mg/m^3), and air quality index (102.5). The air quality index showed a strong positive correlation with particulate matter in most cities in the province. All primary pollutant concentrations and air quality index were higher during winter, compared to ozone in summer. From temporal analysis it was evident that particulate matter, sulphur dioxide, carbon monoxide, and air quality index reached maximum during January, and nitrogen dioxide and ozone during December and June, respectively. All air pollutant concentrations and air quality index from 2014 to 2018 were on a decreasing trend, except for urban ozone, which increased by 9.6 %.

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1. Background

Rapid industrialization and development have made China one of the fastest developing economies in the world. According to World Bank data, the annual GDP growth of China was 5.9 % in 2019 (World Bank, 2021). This quick growth is because of increased production and industrial activity throughout China, resulting in the release of vast quantities of primary pollutants and other chemical compounds into the atmosphere. Many studies have shown a link between air pollutants and human health problems. Some common ailments are related to respiration, heart disease, Parkinson's disease, mental health, and higher mortality rates (Xia et al., 2017; Mishra, 2017; Yin et al., 2017; Chen et al., 2017; Shin et al., 2018; Xue et al., 2019; Sadigh et al., 2021). Air pollution particles also have the potential to penetrate the foetal side of the placentas (Mostofie et al., 2014; Carrington, 2019). A recent study has shown that fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) strongly promote the transmission of SARS-CoV-2 virus (COVID-19) in air (Li et al., 2020a). According to United Nations Environment Programme (UNEP), 6.5 million people prematurely die every year due to outdoor and indoor air pollution (UN Environment Programme, 2017). China introduced ambient air quality standards in 2012 (GB 3095-2012) in a phased manner, with full enforcement in 2016 (Air Quality Standards, 2018). The classified primary standards for special regions (Class 1) and urban areas (Class 2), World Health Organization (WHO) guidelines and the Jiangsu Province compliance rate in 2017 are given in Table 1 (WHO, 2021; Liu and Gao, 2018).

Nanjing is one of the thirteen cities (Figure 1) in the Jiangsu Province located along the Yangtze River delta and is the capital of Jiangsu Province in China. Major coal consumers in Nanjing are power plants, petrochemical industries, steel and cement manufacturing units (Liu and Gao, 2018). Other main industries in the province are electronics, chemicals, textiles, medical products, and general manufacturing (China Provinces, 2016). In the past few decades, with increased industrial development and urbanization, vehicle exhaust and gas emissions have increased. This has resulted in an increase in particulate matter and other gaseous pollutants in the atmosphere. The frequency of haze occurrences in this region has also increased, especially in large cities (Yan et al., 2019). The air quality is seldom consistent and changes from one region to another. The coastal cities, Nantong, Yancheng and Lianyungang had better air quality compared to other cities because of the geographical location and wind direction. The cities in the south of the province (Suzhou, Wuxi and Changzhou) had better air quality than the cities in the north (Xuzhou, Suqian and Huai'an) because of improved economic conditions, less dependence on coal, and implementation of energy saving policies. However, in the cities along the west of the province (Nanjing, Huai'an, Xuzhou and Suqian), air quality declined (Liu and Gao, 2018). The distribution and movement of pollutants are also significantly influenced by the meteorological conditions of the location. With implementation of strict air quality control measures, the air quality index (AQI) and concentrations of primary pollutants have decreased over the years, with annual high values occurring during winter and low values during summer (Wang et al., 2021a). Correlation coefficient studies among air pollutants and the air quality index (AQI) have shown both positive and negative correlation with ozone (O_3).

The current work intends to study the spatial, temporal and seasonal variation of the prominent six criteria air pollutants and AQI in the thirteen cities of the Jiangsu Province from 2014 to 2018 and its correlation. Objectives of the study were to determine the cities, seasons and geographical locations with maximum values of AQI, pollutant concentration and correlation strength between them.

2. Materials and Methods

The Jiangsu Province is situated in the eastern part of China; its terrain is flat and located in a climatic transition zone between north and south China (Song et al., 2019). In 2018, the total population was estimated to be 80.5 million, with the total area of 102,600 km^2 (City population, 2019). The air pollution data for the cities in the Jiangsu Province were obtained from the China air quality online monitoring and analysis platform (aqistudy.cn). The average monthly mass concentration of atmospheric pollutants was calculated by taking the mean of everyday data (Yin et al., 2019; Li et al., 2020b). The main criteria air pollutants studied were particulate matter ($PM_{2.5}$, PM_{10}), ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and air quality index (AQI) to determine the level of pollution. The AQI values used for comparison were based on the Chinese Ministry of Environmental Protection standard (HJ 633-2012) given in Table 2 (Qiao et al., 2015; MEP, 2012). The thirteen cities of the Jiangsu Province are Xuzhou (XZ), Lianyungang (LG), Changzhou (CZ), Wuxi (WX), Suzhou (SZ), Yancheng (YC), Nantong (NT), Suqian (SQ), Huai'an (HU), Nanjing (NG), Yangzhou (YZ), Zhenjiang (ZJ), Taizhou (TZ) and shown in Figure 1. Furthermore, the cities were grouped based on their geographical location as follows: Northern cities (Xuzhou, Lianyungang), Southern cities (Changzhou, Wuxi, Suzhou), Eastern cities (Yancheng, Nantong), Western cities (Suqian, Huai'an, Nanjing) and Central cities (Yangzhou, Zhenjiang, Taizhou). The data correlation analysis was performed using the statistical software SPSS 25, IBM Corporation. Bivariate associations between air pollution data and AQI were performed using Spearman's correlation coefficient. The climatic characteristics were considered taking into account the four seasons, spring (March, April and May), summer (June, July and August), autumn (September, October and November) and winter (December, January and February). The correlation coefficient was interpreted based on the following: 0.90–1.0 very strong correlation; 0.70–0.89 strong correlation; 0.50–0.69 moderate correlation; 0.30–0.49 weak correlation, and < 0.30, very weak correlation (Mukaka, 2012).

Table 1. Chinese air pollution primary standards, WHO guidelines and Jiangsu Province compliance rate.

Pollutant	Averaging time	Chinese Limits (2012) Class 1	Chinese Limits (2012) Class 2	WHO (2021)	Jiangsu Province (2017)
$PM_{2.5}$ (μg/m^3)	24-hour	35	75	15	–
	Annual	15	35	5	49
PM_{10} (μg/m^3)	24-hour	50	150	45	–
	Annual	40	70	15	81
O_3 (μg/m^3)	8-hour	100	160	100	177
NO_2 (μg/m^3)	24-hour	80	80	25	–
	Annual	40	40	10	39
SO_2 (μg/m^3)	24-hour	50	150	40	–
	Annual	20	60	–	16
CO (mg/m^3)	24-hour	4	4	4	1.5

Figure 1. Cities in the Jiangsu Province in China.

Table 2. Chinese air quality index standards

AQI range	Air quality conditions
0 – 50	Good
51 – 100	Moderate
101 – 150	Lightly polluted
151 – 200	Moderately polluted
201 – 300	Heavily polluted
> 300	Severely polluted

3. Results and Discussion

Spatial distribution of air pollutants

The average values of air pollutants and AQI for five successive years from 2014 to 2018 across various cities in the Jiangsu Province are presented in Figure 2. The data indicates Xuzhou city to have the highest concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO, and AQI. When compared with the class 2 annual Chinese limits, $PM_{2.5}$ and PM_{10} concentrations were 81.1 % and 64.9 % higher, whereas SO_2 and CO concentrations were 50 % and 70.5 % lower than the prescribed limits. The AQI value (102.5) was in the range of lightly polluted as per the Chinese air quality index. Xuzhou city is located in the northern part of the Jiangsu Province and is the second largest steel producer in China (Xu and Mason, 2018). An increase in air pollution is attributed to anthropogenic sources such as coal mining and combustion and the presence of heavy industries (Chen et al., 2017). A similar observation was made by Liu and Gao (2018), who determined that Xuzhou's air quality declined by 16.3 % between April 2015 and March 2018. The NO_2 concentration was found to be greatest in Suzhou located in the south of the province (24.8 % greater than the class 2 annual Chinese limits). This is attributed to the increase in vehicle emissions in addition to other industrial activities. The highest concentration of ozone (107 μg/m^3, 33.1 % lower than the class 2 Chinese limits), which is a secondary pollutant, was found in Huai'an city located in the western part of the province. This observation was in line with the study by Ma et al. (2019). This suggests the availability of suitable primary pollutants and favourable climatic conditions for the formation of O_3.

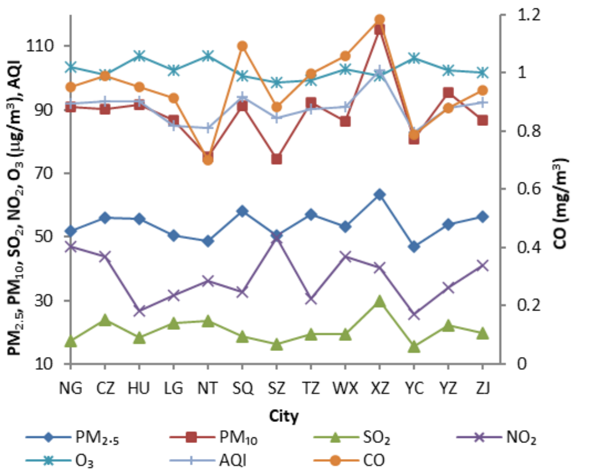

Figure 2. Five-year average values of air pollutants and AQI in Jiangsu Province cities during 2014 - 2018

The AQI values are correlated with various pollutants in different cities in the Jiangsu Province and are presented in Figure 3. It can be seen that the AQI exhibited a strong positive correlation with $PM_{2.5}$ and PM_{10} in most of the cities in the province. For $PM_{2.5}$, ten out of thirteen cities and for PM_{10}, eleven out of thirteen cities had p-values > 0.7. In contrast, only one city for SO_2 and two cities for CO had p-values > 0.7. The results imply that $PM_{2.5}$ and PM_{10} have a greater contribution to AQI compared to SO_2 and CO. A similar trend was also observed by Xu et al. (2020). NO_2 exhibited moderate to weak positive correlation. Ozone, on the other hand, was mostly negatively correlated, and was weak to very weak with AQI, with the highest correlation coefficient value in Xuzhou city. The primary sources of $PM_{10\text{-}2.5}$ include suspended road dust, brake emissions, industrial processes, construction activities, biological particles, sea spray, surface soils and biomass burning (Cheng et al., 2015). The primary anthropogenic source of SO_2 is the burning of fossil fuels, and its reduction in the atmosphere correlates to the reduction in industrial activity (Wang et al., 2018). The correlation coefficient results indicated a predominantly moderate (8/12 cities) relationship, highlighting active industrial activity in the province. NO_2 pollution is attributed to transportation fuels, burning of fossil fuels in power plants and other industrial facilities (Rohde and Muller, 2015). The contribution of NO_2 to AQI seems to be moderate (6/13 cities) to weak and is not significant as compared to PMs and SO_2. Major carbon monoxide sources are connected to residential burning, the iron and steel industries, gasoline vehicles, and industrial boilers (Zheng et al., 2018). The coefficient values indicate strong correlation in Huai'an and Taizhou cities in the western and central regions of the Jiangsu Province. Other cities had moderate (6/11 cities) to weak relations with AQI. This is because the extent of pollutants released into the atmosphere varies between cities and depends on industrial development and the number of vehicles on the road. Ozone, on the other hand, is produced by the reaction between carbon monoxide, volatile organic compounds, and nitrogen oxides in the presence of sunlight (Lu et al., 2018).

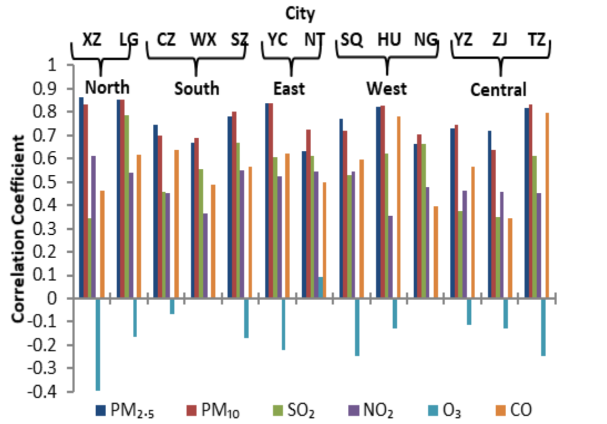

Figure 3. Spearman's correlation coefficient relating AQI and air pollutants in Jiangsu Province cities during 2014 - 2018

The seasonal variations of $PM_{2.5}$, NO_2, and O_3 across the cities in Jiangsu Province are shown in Figures 4–6. It can be seen from Figure 4 that the maximum concentration of $PM_{2.5}$ was during winter, and the peak value was in Xuzhou (96.7 µg/m³). The lowest concentration was during the summer, with Yancheng having the lowest concentration of 31.7 µg/m³. Similar findings have also been reported by Song et al. (2019). In a study conducted by Zhang and Cao (2015) in 190 cities in China, $PM_{2.5}$ was maximum during summer with a population-weighted mean value of 61 µg/m³. Average $PM_{2.5}$ concentration values during spring, summer, autumn and winter were 54.5 µg/m³, 38.1 µg/m³, 45.8 µg/m³ and 77.9 µg/m³, respectively. This is in accordance with observation by Yu et al. (2019).

Seasonal change in NO_2 concentration across the cities in the Jiangsu Province is presented in Figure 5. NO_2 in the atmosphere throughout Jiangsu Province was highest during winter, with the maximum value of 60 µg/m³ in Suzhou. A similar trend was also noticed by Guo et al. (2020).

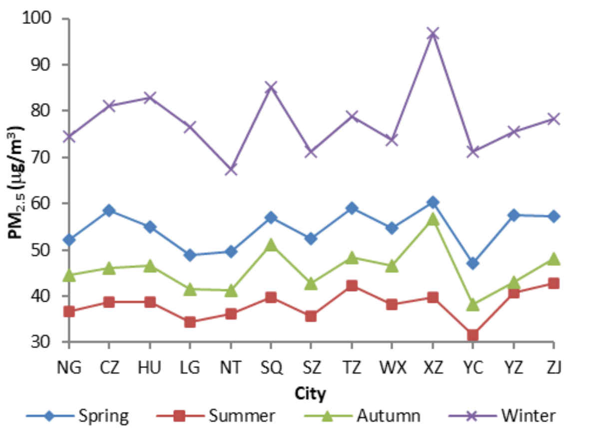

Figure 4. Seasonal variation of PM2.5 across the cities in Jiangsu Province during 2014 - 2018

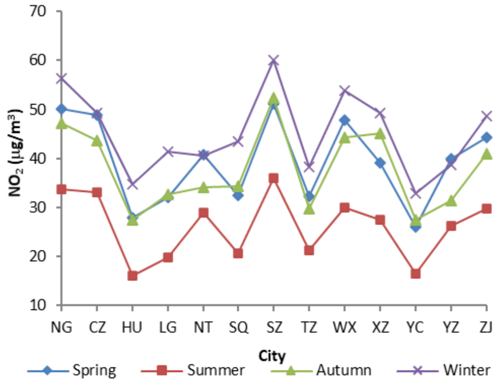

Figure 5. Seasonal variation of NO2 concentration across the cities in Jiangsu Province during 2014 - 2018

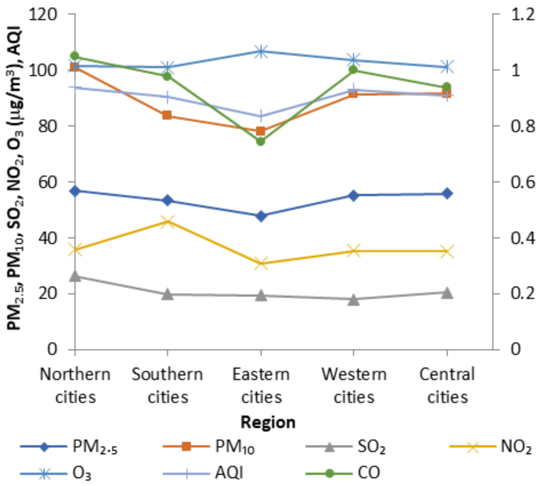

Figure 6. Seasonal variation of O3 concentration across the cities in Jiangsu Province during 2014 - 2018

In addition to the NO_x gases produced by the coal power stations, motor vehicles are another important source. Suzhou city has about 3.55 million cars and ranks fifth among the top ten cities in China having the most number of cars (Yanfang, 2018). It is worth noting that the variation in NO_2 concentration between spring and autumn was minimal and relatively close to the winter values, suggesting that climatic conditions have minimal effect on atmospheric NO_2 concentration. The average ozone concentration (Figure 6) reached maximum during summer and spring and minimum during winter. This is because of the absence of the required sunlight for the formation of urban ozone. High concentrations were observed in Suqian, Wuxi, Huai'an, Xuzhou, and Zhenjiang cities during the summer.

Changes in air pollutant concentration and AQI in different regions in Jiangsu province are presented in Figure 7. The average particulate matter ($PM_{2.5}$, PM_{10}), NO_2, CO concentrations and AQI were lowest in the eastern cities (Yancheng, Nantong) adjoining the coastal region. This is because of the presence of land and sea breezes, which dissipate the pollutants (Ma et al., 2019).

opposite trend was observed with O_3, which is probably due to the suitable weather conditions for the formation and wind movement of O_3 from inland regions to the coastal cities, especially by the sea-land breezes (Wang et al., 2017). The average SO_2 values were found to be lower in the western cities (Suqian, Huai'an, Nanjing). This was consistent with the study that showed Nanjing city to have lower SO_4^{2-} pollution (Zhang et al., 2018). Noticeably high values of $PM_{2.5}$, PM_{10}, SO_2, CO, and AQI were found for two northern cities (Xuzhou, Lianyungang). Although Lianyungang is located along the coastline with relatively low levels of pollution, its proximity to Xuzhou with higher pollution levels has elevated the region's pollution concentration. In addition, air pollution in neighbouring Shandong Province is also likely to affect pollution levels in the region. Significantly high levels of NO_2 were observed in the southern cities (Changzhou, Wuxi, Suzhou) with major contributions from Suzhou. Song et al. (2019) have also shown that high values of NO_2 occur at Changzhou (49.6 µg/m^3) and Suzhou (46.6 µg/m^3). Similar observations were also made by Wang et al. (2021b).

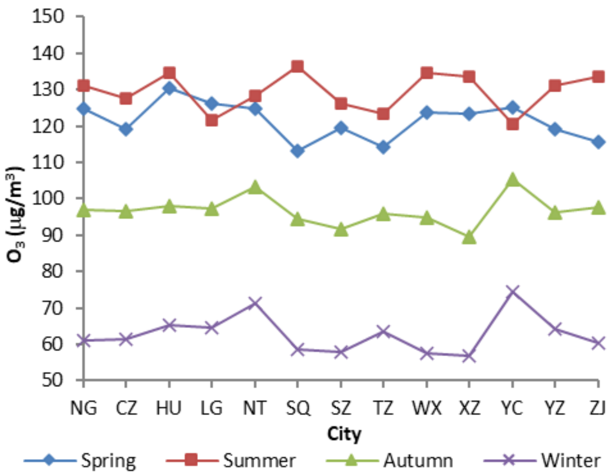

Figure 7. Variation of pollutant concentration and AQI in different regions of Jiangsu Province during 2014 - 2018

Temporal distribution of air pollutants

The monthly variation in pollutant concentrations is presented in Figure 8. The average $PM_{2.5}$ concentration was maximum in January and minimum during August, and a similar trend was also observed with the PM_{10} concentration. The concentration of SO_2, CO, and AQI were maximum in January and minimum during July (SO_2, CO) and October (AQI), while NO_2 was maximum in December and minimum during August. The O_3 concentration profile had an opposite trend when compared with other pollutants, which was consistent with the observation by Song et al. (2019). The peak was during June in summer and the lowest was in December during winter. A small inflection for $PM_{2.5}$, O_3, and AQI can be seen during June. This could suggest the existence of a relationship between AQI and O_3 and $PM_{2.5}$.

The pollutant concentrations ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and AQI) tend to be high during January and December (Figure 8 and 9). During winter, the pollutants remain in the air for a longer time period, and the probable cause is due to temperature inversion apart from other anthropogenic sources (Huaqing et al., 2016). On the other hand, the minimum occurred during the summer months of July and August. The decrease in pollution levels can be strongly attributed to weather changes in the region. The only exception was with O_3, which had an opposite trend, exhibiting a maximum during summer and a minimum during winter due to the decrease in solar radiation, which is a prerequisite for its formation. AQI showed a decreasing trend during summer and autumn, which is consistent with the analysis by Song et al. (2019).

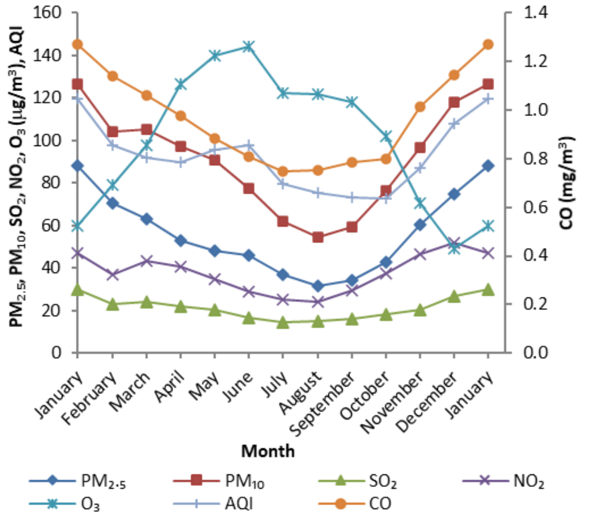

Figure 8. Monthly variation of air pollutants and AQI in Jiangsu Province during 2014 - 2018

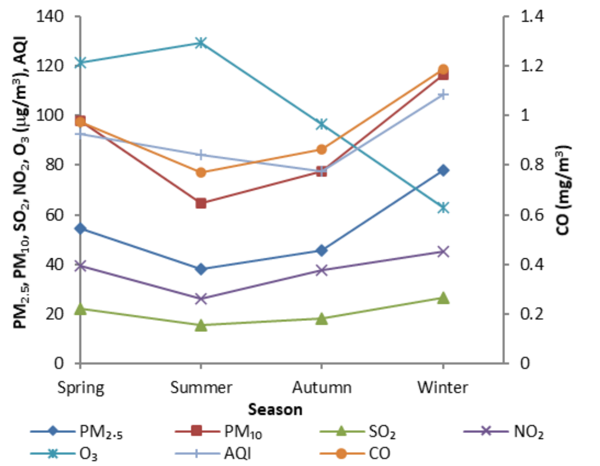

Figure 9. Seasonal variation of air pollutants concentration and AQI in the Jiangsu Province during 2014 - 2018

Variation of air pollutants and AQI from 2014 to 2018 in the Jiangsu Province is illustrated in Figure 10. With the implementation of air pollution control policies in China (Clean Air Action by China State Council in 2013), a decrease in the pollutant concentration can be seen for $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and AQI by 29.7 %, 30.2 %, 58.1 %, 0.80 %, 19.6 %, and 12.9 % over the years. Previous studies by Fan et al. (2020) and Li et al. (2019) highlight similar trends in the study of air pollutants in different Chinese cities. Maximum reduction was achieved for SO_2 and minimum for NO_2. The difference in the reduction rates of pollutants depends on the distribution of the sources and the mitigation measures adopted (Zheng et al., 2018). Significant reductions in particulate matter could be attributed to the adoption of efficient dust collectors in large industries. The raw coal burnt in Jiangsu Province contains about 0.64 % sulphur content. With the utilization of flue gas desulfurization (FGD) units in power plants, substantial reductions in SO_x can be achieved (Hussain and Luo, 2019). Even though the selective catalytic reduction (SCR) process is effective in reducing the NO_x emissions from the flue gases, the NO_2 concentration in the atmosphere increased by 7.4 % in 2017 and consequently declined in 2018. CO reduction can be enhanced through the use of efficient burners in industries, replacement of coal with natural gas and electricity, and replacement of old vehicles with newer models that meet stringent emission standards. The urban O_3 concentration on the other hand, increased by 9.6 % and peaked in 2017 (13.1 %). This suggests a strong relationship with the high concentrations of NO_2 observed in 2017. The trend observed with NO_2 and O_3 was also reflected in the AQI curve.

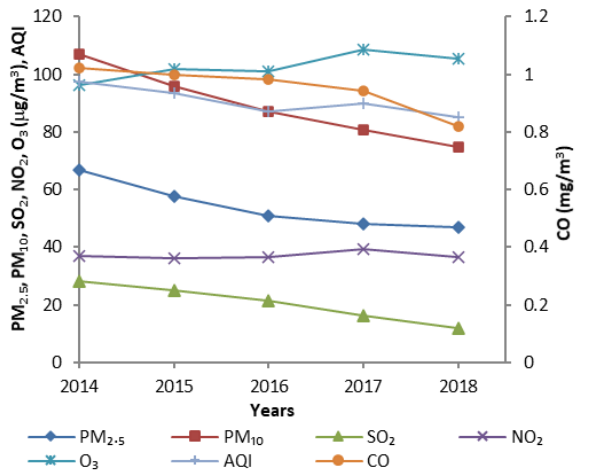

Figure 10. Variation of air pollutants concentration and AQI in the Jiangsu Province from 2014 to 2018

4. Conclusion

The comprehensive data analysis identified the cities, seasons and geographical locations in the Jiangsu Province with high values of AQI and air pollutants and their relationship. Spatial analysis indicated high average values of $PM_{2.5}$ (63.4 µg/m³), PM_{10} (115.4 µg/m³), SO_2 (30 µg/m³), CO (1.18 mg/m³), and AQI (102.5) in Xuzhou city located in the northern part of the province. Maximum average values of NO_2 (49.9 µg/m³) and O_3 (107 µg/m³) were observed in Suzhou and Huai'an cities located in the south and western part of the province. The correlation between AQI and particulate matter ($PM_{2.5}$ and PM_{10}) was predominantly positive and strong, whereas with ozone it was negative and weak. All primary pollutant concentrations and AQI values were higher during winter, while ozone during summer. Temporal analysis indicated $PM_{2.5}$, PM_{10}, SO_2, CO, and AQI to be high during January, and NO_2 and O_3 in December and June. All pollutant concentrations and AQI were found to decrease from 2014 to 2018 except O_3. In order to reduce pollutant concentrations and comply with stringent air pollution standards, existing air pollution control equipment would have to be updated or a transition to new technologies is suggested.

Conflict of interest
The authors declare that they have no conflict of interest.

Grant Disclosures
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Competing Interests
The author declares there are no competing interests, regarding the publication of this manuscript.

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