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Analysis of Air Quality Change Characteristics and Correlation with Meteorological Factors in Yangtze River Delta City Cluster

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Abstract: *This study analyzed the changes and correlations of AQI and six basic pollutants ($PM_{2.5}$, PM_{10}, SO^2, N^2, CO, O^3) in the Yangtze River Delta city cluster from 2016 to 2019 based on air pollutant concentration monitoring data and meteorological factors. The analysis used Kriging interpolation and Pearson correlation methods. The main findings were: (1) The air quality of the study area improved over time; $PM_{2.5}$, PM_{10}, N^2 and CO concentrations were higher in winter; O^3 concentration was higher in summer; SO^2 concentration was relatively stable across seasons; O^3 concentration showed an inverted "U" pattern over time, while the other pollutants showed a "U" pattern. (2) Spatially, AQI was higher in the northwest and lower in the southeast of the study area; $PM_{2.5}$ and PM_{10} concentrations had high spatial similarity with AQI. (3) The correlations between each pollutant concentration and meteorological factors varied; precipitation and air temperature had significant correlations with all six pollutants; relative humidity had a more significant correlation with PM_{10}; the other factors had no significant correlations with the pollutants.*

Keywords: *AQI; air quality; spatial and temporal distribution; meteorological factors; Yangtze River Delta city cluster*

1. Introduction

Since the industrial revolution, environmental pollution problems have gradually emerged, and atmospheric environmental pollution has become more prominent, thus triggering academic research on atmospheric pollution. 1976, the United States established the evaluation index PSI (pollution standard index) with CO, N^2, SO^2, oxidant and particulate matter as evaluation factors, and estimated the degree of atmospheric pollution in Tehran and other areas(Cheng et al,2007;Hassanzadeh et al,2012.).In 1996, China established the API (Air Pollution Index), an evaluation index with SO^2, N^2 and PM_{10} as evaluation factors, for the comprehensive evaluation of the air environment according to the characteristics of air pollution and pollution prevention priorities in China. Related scholars have studied the spatial and temporal characteristics of API at the national, regional, and municipal levels(Liu & Fu,2018;Liu et al,2018;Xiao et al,2018.Xie et al,2014;Qi et al,2014;Fu & Li,2020;Su et al,2019;Shi et al,2018).With the changes in China's socio-economic development and environmental protection requirements, the attention to the air environment has shifted from mainly pollution control to more focus on the improvement of environmental quality. For this reason, China revised its ambient air quality standards in 2012, and also established AQI (Air Quality Index), an evaluation index with $PM_{2.5}$, PM_{10}, SO^2, N^2, CO, and O^3 as evaluation factors, to provide a more rigorous and precise evaluation of ambient air quality. In recent years, relevant scholars at home and abroad have also analyzed the spatial and temporal variation characteristics and influencing factors of AQI at the national, city cluster and municipal level (Zhao et al,2020;Lang et al,2021;Li et al,2018;Li et al,2019;Ye & Jin,2019;Zhao et al,2020;Zheng et al,2020;Ede & Edokpa,2015;Chen et al,2020;Ren et al,2019;Bencardino et al,2018).The results of those studys showed that the main factors affecting AQI are natural factors such as precipitation, sunshine, wind direction, and topography and anthropogenic factors such as agricultural straw burning, fireworks, automobile exhaust, and industrial smoke and dust emissions(Liu et al,2018;Liu et al,2014;Kumar et al,2021;Yang et al,2016;Yang & He,2016;Yi et al,2021.Wang et al,2023)[1-5].

Yangtze River Delta region is China's highest level of urbanization, economic development, in China's modernization and all-round opening pattern in a pivotal position. In recent years, as the Yangtze River Delta region air pollution prevention and control work continued to promote the overall improvement of regional air quality. However, the current regional air environment situation was still severe, the air quality improvement effect was not solid. Due to the large energy consumption of resources and high intensity of pollutant emissions, air pollution in the Yangtze River Delta presented regional, compound and compressed characteristics(Chen & Li ,2021). Therefore, air pollution in the Yangtze River Delta has become a research hotspot for related scholars, such as Tan et al.(2021)analyzed the influence of black carbon on surface ozone in the Yangtze River Delta from 2015 to 2018; Gao et al.(2021) analyzed the pollution characteristics, transport trajectories and influencing factors of $PM_{2.5}$, O^3 and C^2 as individual pollutants in the Yangtze River Delta region; Xu et al.(2016) constructed a concentration estimation model of PM_{10} using satellite remote sensing data, based on which the spatial and temporal distribution characteristics of PM_{10} were analyzed. In summary, scholars have used different pollutants to analyze the air quality conditions in the Yangtze River Delta region, and their research results had important reference values for further research on air pollution problems in the Yangtze River Delta region. However, there is a lack of comprehensive studies on the spatial and temporal variations of AQI and the concentrations of six basic pollutants, and there are even fewer relevant studies on the Yangtze River Delta urban agglomerations.City cluster are important engines for promoting regional economic and social development, but their air pollution problems are made more prominent due to population growth, industrial agglomeration and high energy consumption. Therefore, this paper took the Yangtze River Delta urban agglomeration as the research object, and used AQI and six basic pollutant concentration monitoring data and combines meteorological data such as precipitation, temperature, relative humidity, air pressure, and wind speed to comprehensively analyze the characteristics of air pollution changes in the Yangtze River Delta urban agglomeration and the correlation between them and meteorological factors from 2016 to 2019[6-9].

2. Regional overview

The Yangtze River Delta city cluster is a triangle-shaped metropolitan region in Eastern China, covering Shanghai and parts of Jiangsu, Zhejiang and Anhui provinces. It has a subtropical monsoon climate with an average annual temperature of 14-18°C and annual precipitation of 1000-1500mm, mainly concentrated in summer and autumn. The terrain is low and flat with an average elevation of about 50m. The city cluster consists of 26 cities , namely Shanghai; Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yancheng, Yangzhou, Zhenjiang and Taizhou in Jiangsu; Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Jinhua, Zhoushan and Taizhou in Zhejiang; and Hefei, Wuhu, Maanshan, Tongling, Anqing, Chuzhou, Chizhou and Xuancheng in Anhui. The total area is about 211,700km2 and the total population is about 160 million people. The Yangtze River Delta urban agglomeration is one of the three major urban agglomerations in China (Xia C et al.2022), with rapid economic growth and urbanization. It is not only an important global advanced manufacturing base but also one of the largest concentrations of foreign population. In 2019, the urbanization rate of the Yangtze River Delta urban agglomeration was about 68.4%, 7 percentage points higher than the national population urbanization rate (60.6%), and the gross national product was 20.37 trillion yuan, accounting for 20.65% of the GDP. The city cluster has a pivotal strategic position in the overall national modernization and all-round opening pattern(Xue ,2021.Ran et al,2022).

3. Data sources and research methods

3.1. Data source

We obtained the AQI values and daily average concentrations of $PM_{2.5}$, PM_{10}, O^3, SO^2, N^2, and CO for 2016-2019 for the Yangtze River Delta city cluster from the China Air Quality Online Monitoring and Analysis Platform (https: //www.aqistudy.cn/). We also obtained meteorological data, including precipitation, temperature, barometric pressure, relative humidity, and wind speed, from China Meteorological Data Network (http: //data.cma.cn /site /index.html). We collected socio-economic data from the 2019 National Economic and Social Development Statistical Bulletin of each region. We divided the Yangtze River Delta urban agglomeration into four seasons based on the research results of Yang Mian et al(2017), as follows: spring (March-May), summer (June-August), autumn (September-November), and winter (December-February)[10-15].

3.2. Research methods

3.2.1. Kriging method

The Kriging method, also known as spatial local interpolation or Gaussian process regression(Cressie N, 1990), is an interpolation method for unbiased optimal estimation of regionalized variables in a finite region based on variational function theory and structural analysis (Marinoni O, 2003). This method first determines the range of distances that have an influence on the value of a point to be interpolated, and then uses the sampling points within this range to estimate the attribute values of the point to be interpolated. The calculation formula is as follows.

$$z(x_0)=\sum_{i=1}^{n}\lambda_i z(x_i) \tag{1}$$

Where: z(x0) is the estimated value at (x0, y0), λi is the weight coefficient, z(xi) is the observed value at xi, and n is the number of observation points.

According to the kriging unbiased, minimum variance condition the weight coefficients λi (i=1,2,...... ,n) satisfy the relation.

$$\sum_{i=1}^{n}\lambda_i = 1 \tag{2}$$

$$\begin{cases}\sum_{i=1}^{n}\lambda_i c(x_i,x_j)+\mu=c(x_0,x_j)\;(j=1,2,......,n)\\ \sum_{i=1}^{n}\lambda_i=1\end{cases} \tag{3}$$

where C(xi,xj) is the covariance function of z(xi) and z(xj).

3.2.2. Pearson correlation coefficient

Pearson correlation analysis is used to analyze the linear relationship between two variables, mainly by calculating the correlation coefficient to reflect the strength and direction of the relationship. The correlation coefficient is defined as follows:

$$r=\frac{\sum_{i=1}^{n}(X_i-\overline{X})(Y_i-\overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i-\overline{Y})^2}} \tag{4}$$

The larger the absolute value of the correlation coefficient r indicates the stronger the correlation, with the value of r between [-1,1], r>0, indicating that the two elements are positively correlated, r<0, indicating that the two elements are negatively correlated, and r=0, indicating that the two elements are not linearly correlated.

3.2.3. Distance average analysis

The distance average refers to the difference between a value in a series and the mean, and can be positive or negative. It is easy to use and intuitive, and is used to determine whether the data for a given time period or epoch is high or low relative to the average of that data for a given period[16-21].

4. Results and Analysis

4.1. Spatial and temporal variation characteristics of AQI

4.1.1. AQI temporal variation characteristics

The annual average AQI in the Yangtze River Delta urban agglomeration from 2016 to 2019 ranged from 49 to 100, and none of them exceeded the limit value of 100 according to the GB 3095-2012 ambient air quality standards1. Based on the annual average kernel density of AQI in the Yangtze River Delta city cluster from 2016 to 2019 (Figure 1), the kernel density of AQI in the range of 80-100 increased from 2016 to 2017, and the kernel density in the range of 70-80 decreased, indicating a deterioration of air quality from 2016 to 2017. In contrast, the kernel density of AQI in the 80-90 range decreased significantly from 2017 to 2018, while the kernel density in the 70-80 range increased significantly. This indicates an overall improvement in air quality from 2017 to 2018. However, the kernel density in the range of 60-80 decreased significantly from 2018 to 2019, while the kernel density in the range of 80-90 increased, indicating a worsening of air quality in this period. Overall, the AQI of the Yangtze River Delta urban agglomeration fluctuated and declined from 2016 to 2019, and the air quality improved as a whole.

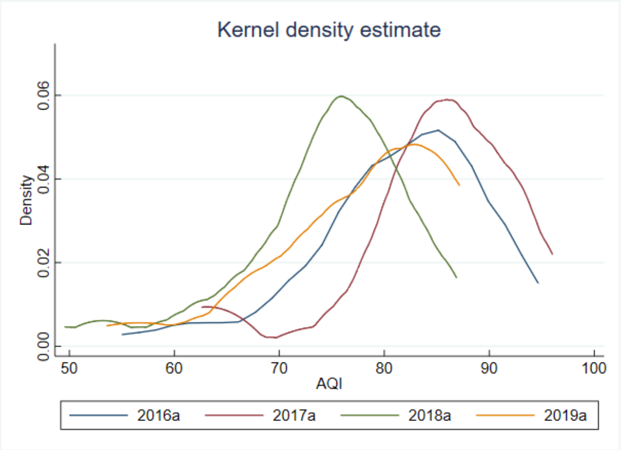

Figure 1: Kernel density of annual average AQI values in the Yangtze River Delta city cluster, 2016-2019

The seasonal trend of AQI can be seen in Figure 2: AQI from 2016 to 2018 showed a pattern of "high in spring and winter, low in summer and autumn", while AQI in 2019 exhibited a pattern of "high in spring and low in winter, moderate in summer and autumn". A comparison of the four-season averages of AQI from 2016-2019 revealed that AQI decreased in all four seasons in 2018 compared to 2016 and 2017, with more significant reductions in spring, summer and winter. The lowest AQI and the most remarkable decrease were observed in winter 2019. This was mainly attributed to the impact of the COVID-19 pandemic, which curbed energy consumption and air pollution emissions in most areas by shutting down work and production as well as reducing traffic flow, thus leading to a significant improvement in air quality[22-28].

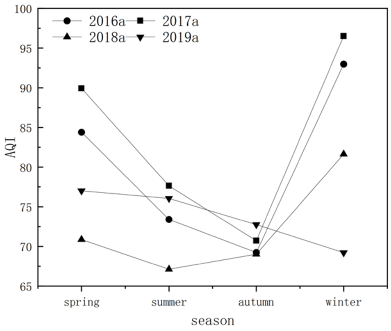

Figure 2: Quarterly trend of AQI in Yangtze River Delta city cluster, 2016-2019

4.1.2. Spatial variation characteristics of AQI

The spatial distribution characteristics of AQI in the Yangtze River Delta urban agglomeration from 2016 to 2019 were analyzed using the Kriging method1, a geostatistical technique of interpolation based on Gaussian process governed by prior covariances2 (Figure 3). As shown in Figure 3, the spatial differences of AQI in the Yangtze River Delta urban agglomeration from 2016 to 2019 were significant, with the overall distribution characteristics of "high in the northwest and low in the southeast". The areas with high AQI values and higher areas were mainly located in the northwest, and the areas with low AQI values were mainly located in the southeast. This was mainly due to the relatively concentrated industries in the northwestern cities, which had higher industrial emissions and lower forest coverage, resulting in poorer air quality, while the southeastern coastal cities had a humid climate and high vegetation coverage, which, combined with good air mobility and high precipitation, were conducive to the diffusion and dilution of pollutants and generally better air quality. In terms of its changes, the range of high value area and higher value area showed a shrinking trend from 2016 to 2019, and the range of low value area and lower value area showed a gradual expansion trend, and mainly to the southwest and northeast, further indicating that the air quality of the Yangtze River Delta urban agglomeration was improved.

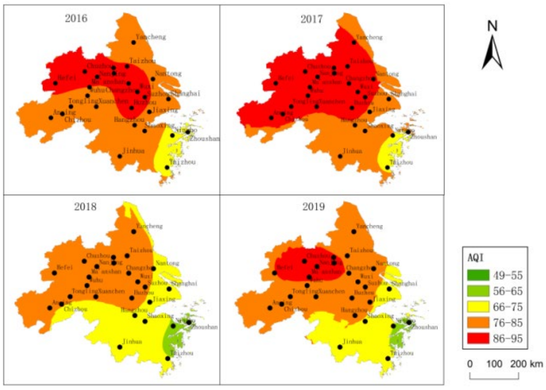

Figure 3: Spatial distribution of annual average AQI values in the Yangtze River Delta city cluster, 2016-2019

The seasonal spatial distribution of AQI also varied significantly (Figure 4), showing an overall spatial distribution pattern of “high in spring and winter, low in summer and autumn”. In terms of its variation, the areas with high and higher AQI values were more widely distributed in winter, followed by spring, and the areas with low and lower AQI values were dominant in autumn. It can be inferred that the northwest was the key area for air pollution prevention and control in the Yangtze River Delta city cluster, and winter was the key time point for prevention and control[29-37].

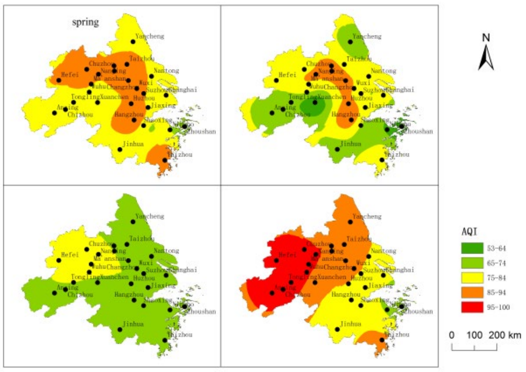

Figure 4: Quarterly spatial distribution of AQI in the Yangtze River Delta city cluster, 2016-2019

4.2. Spatial and temporal variation characteristics of pollutant concentrations

4.2.1. Characteristics of temporal variation of pollutant concentrations

We compared the anomaly maps of six basic pollutants in 2016-2019 (Figure 5) and found (Figure 5) that from 2016 to 2019, the concentrations of all pollutants except O^3 decreased to varying degrees compared to the 4a average value. O^3 concentration fluctuated and increased by 2%. SO^2 concentration showed the largest decrease of 79.22%, followed by CO, while N^2 concentration showed the smallest decrease of only 8.11%.

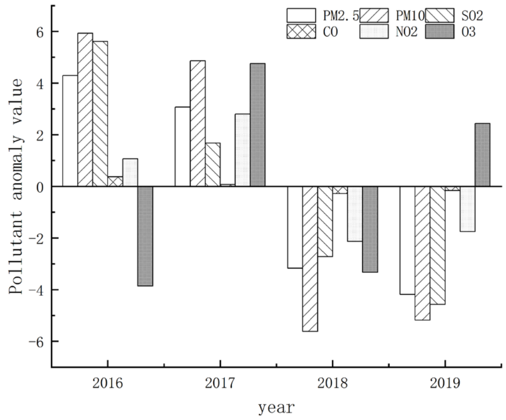

Figure 5: 2016-2019 Yangtze River Delta city cluster 6 basic pollutants anomaly maps

The quarterly distribution of the average concentrations of the six basic pollutants in 2016-2019 (Figure 6) showed that $PM_{2.5}$, PM_{10}, N^2, and CO concentrations were highest in winter and lowest in summer, while O^3 concentration showed the opposite pattern. SO^2 concentration was relatively uniform across all seasons. Regarding their concentration changes, from 2016 to 2019, $PM_{2.5}$, PM_{10}, SO^2, N^2, and CO concentrations in the Yangtze River Delta city cluster exhibited decreasing trends in different seasons, with the most significant decrease occurring in winter. However, O^3 concentrations displayed a fluctuating increasing trend in spring and summer, and a fluctuating decreasing trend in autumn and winter.

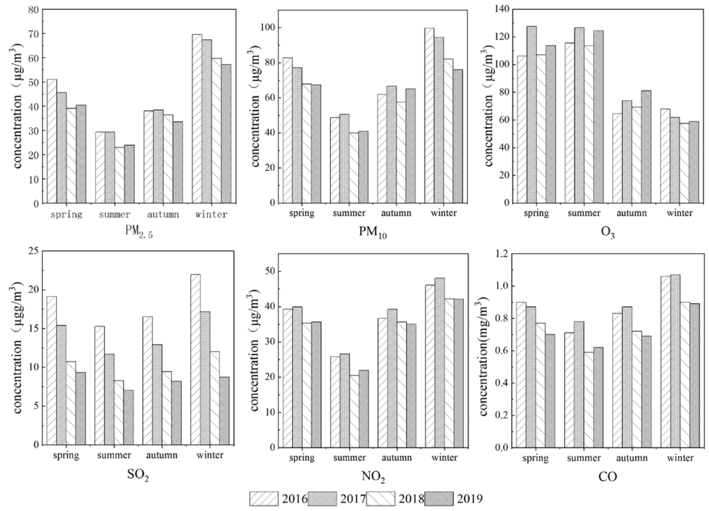

Figure 6: Quarterly variation of the average concentration of six basic pollutants in the Yangtze River Delta urban agglomeration from 2016 to 2019

The average concentrations of the six basic pollutants showed clear monthly trends (Figure 7). All pollutants except O^3 changed in a "U" shape, while O^3 changed in an inverted "U" shape. PM_{10}, $PM_{2.5}$, CO and N^2 had high concentrations in January, followed by a fluctuating downward trend from January to August. They reached their lowest concentrations in August and then gradually increased to reach high concentrations again in December. SO^2 had high concentrations in January and December and low concentrations from June to August. O^3 had low concentrations in December and high concentrations in May and June[38-42].

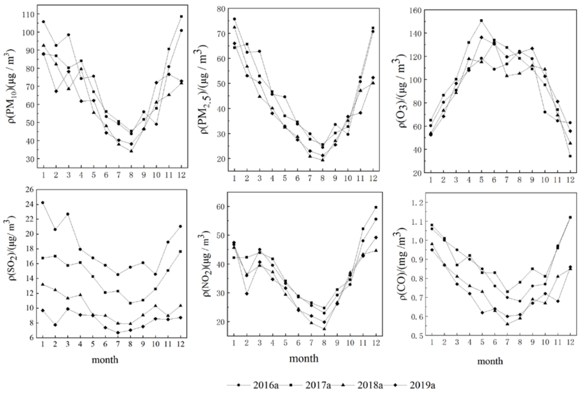

Figure 7: Trend of monthly average concentrations of six basic pollutants in the Yangtze River Delta city cluster, 2016-2019

4.2.2. Spatial distribution characteristics of pollutant concentration

The concentrations of the six basic pollutants showed distinct spatial distribution patterns (Fig 8). The distribution of $PM_{2.5}$ and PM_{10} concentrations was similar to that of AQI, with high values mainly in the northwest and low values mainly in the southeast. O^3 had high values mainly in the northeast and low values mainly in the southwest. N^2 had low values scattered in Yancheng in the northeast and Taizhou, Ningbo and Zhoushan in the southeast, while most other areas had high or higher values. CO had low or lower values mainly in the southeast and along the eastern coast, while most other areas had high or higher values. SO^2 had high values only in Tongling in the southwest, while most other areas had low or lower values. The reason for the high SO^2 value in Tongling was that Tongling was rich in minerals, and a large amount of SO^2 could be produced during mineral combustion and smelting of sulfur-containing ores.

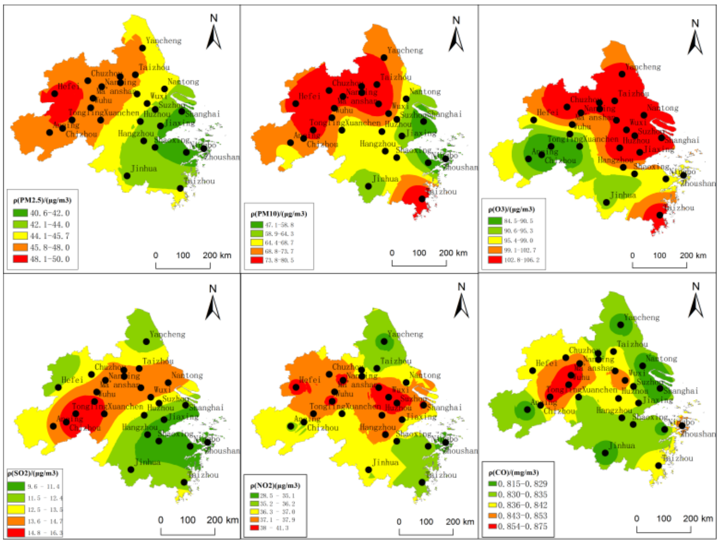

Figure 8: Spatial distribution characteristics of the concentration of six basic pollutants in the Yangtze River Delta urban agglomeration, 2016-2019

4.3. Correlation analysis between atmospheric pollutant concentrations and meteorological factors

Meteorological conditions affect air pollution, and when the sources of pollution are fixed, the pollutant concentrations mainly depend on how they are dispersed, transported and transformed by meteorological conditions (Li et al., 2012). In this paper, we used the Pearson correlation method to analyze the correlation between meteorological factors (precipitation, air temperature, relative humidity, air pressure and wind speed) and air pollutant concentrations in the Yangtze River Delta urban agglomeration. The results are shown in Table 1.

Table 1: Correlation between air pollutant concentrations and meteorological factors in the Yangtze River Delta urban agglomeration

Meteorological factors	$PM_{2.5}$	PM_{10}	SO^2	CO	N^2	O^3
precipitation	-0.822**	-0.894**	-0.854**	-0.818**	-0.849**	0.848**
Temperatures	-0.971**	-0.953**	-0.966**	-0.950**	-0.868**	0.868**
Relative Humidity	-0.497	-0.622*	-0.574	-0.367	-0.378	0.174
Pneumatic pressure	0.353	0.422	0.330	0.289	0.423	-0.189
Wind speed	-0.013	0.038	0.090	-0.185	-0.231	0.287

*$P<0.05$ Significantly correlated at the level; **$P<0.01$ Significantly correlated at the level.

The concentrations of each pollutant and meteorological factors showed different correlations (Table 1). Precipitation and temperature had significant negative correlations with all six basic pollutants at the 0.01 level, except for O^3, which had a significant positive correlation. Relative humidity had a significant negative correlation with PM_{10} at the 0.05 level, meaning that PM_{10} concentrations decreased as relative humidity increased. This was because higher relative humidity increased the water content of particulate matter, which increased extinction and reduced PM_{10} concentration (Li et al., 2007; Gong & Feng, 2012). The other factors did not show significant correlations with the six basic pollutants.

The effects of precipitation and temperature on the concentrations of six basic pollutants in the Yangtze River Delta urban agglomeration were shown in Figure 9: due to the low temperature and low precipitation in January, the air convective movement was weak, which was not conducive to the diffusion and dilution of $PM_{2.5}$, PM_{10} , SO^2 , N^2 , CO , etc., and with the increase of precipitation from February to August, it had a certain cleaning and flushing effect on pollutants (Sun et al,2019); with the increase of temperature, the atmospheric motion was unstable, which improved the diffusion effect of pollutants, thus reducing the concentration of pollutants near the ground, and after September, with the simultaneous decrease in precipitation and temperature, the concentrations of $PM_{2.5}$, PM_{10}, SO^2, N^2, and CO showed a gradual increase. In January, the low temperature and weak solar radiation made photochemical reactions difficult, leading to low O^3 concentrations. Then, as temperature and solar radiation increased, O^3 production accelerated and O^3 concentrations increased (Ding et al,2023.Ye et al, 2017). However, O^3 concentration dropped slightly in the Yangtze River Delta city group due to the rainy season in June, which caused a minor decrease in O^3 concentration compared to May. In July-August, when temperature reached its peak and precipitation was high, the water vapor in the atmosphere reduced the solar radiation and thus slowed down the photochemical reactions, resulting in a decrease in O^3 concentration. After September, as precipitation and temperature decreased, O^3 concentration also decreased[43].

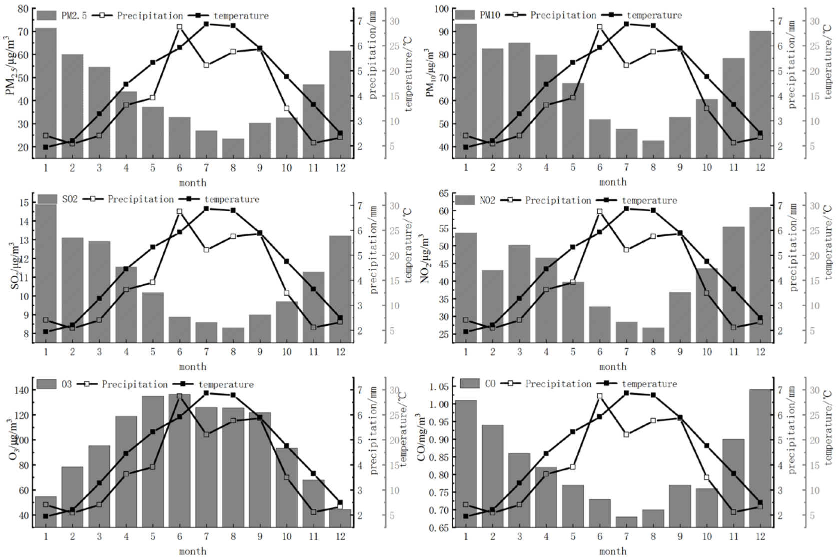

Figure 9: Trends in the concentration of six basic pollutants in relation to precipitation and temperature in the Yangtze River Delta urban agglomeration, 2016-2019

5. Conclusion and discussion

5.1. Conclusion

The air quality of the Yangtze River Delta urban agglomeration generally improved from 2016 to 2019, with the most noticeable improvement in 2018. The AQI varied by season, with high values in spring and winter and low values in summer and autumn from 2016 to 2018, and high values in spring and low values in winter, with moderate values in summer and autumn in 2019. Spatially, AQI had a pattern of high values in the northwest and low values in the southeast. The area with high or higher AQI values decreased from 2016 to 2019, while the area with low or lower AQI values increased. The high or higher AQI values were most prevalent in winter, followed by spring, while the low or lower AQI values were most common in autumn.

Compared with the 4a average, the concentrations of other pollutants decreased by different amounts from 2016 to 2019, except for O^3 concentration, which increased with fluctuations. $PM_{2.5}$, PM_{10}, N^2 and CO had the highest concentrations in winter and the lowest concentrations in summer. O^3 had the opposite pattern, and SO^2 had a uniform distribution across the four seasons. Apart from O^3, the monthly mean concentrations of other pollutants had a U-shaped pattern. Spatially, $PM_{2.5}$ and PM_{10} had high or higher values mainly in the northwest, while O^3 had high values mainly in the northeast.

The analysis of atmospheric pollutants and meteorological factors revealed significant correlations between precipitation and air temperature and 6 basic pollutants. Precipitation and air temperature had significant positive correlations with O^3, and negative correlations with other pollutants. Relative humidity and PM_{10} had significant negative correlations, while other factors did not have significant correlations with 6 basic pollutants.

5.2. Discussion

The above analysis showed that the air pollution in the Yangtze River Delta urban agglomeration improved overall from 2016 to 2019. However, due to population, industrial layout and vegetation coverage factors, $PM_{2.5}$ and PM_{10} concentrations were relatively high in the northwest and O^3 concentrations were relatively high in the northeast, which became the main targets of regional air pollution prevention and control. In addition, because of the seasonal patterns of precipitation and temperature, $PM_{2.5}$ and PM_{10} were less diffused and diluted in winter and O^3 was more formed and accumulated in summer. Therefore, $PM_{2.5}$ and PM_{10} pollution in winter in northwest China and O^3 pollution in summer in northeast China should not be overlooked. Furthermore, as the epidemic prevention and control situation improves and enterprises resume work, air pollutant emissions may increase again, adding pressure for continuous improvement of air quality. Therefore, the prevention and control of air pollution in the Yangtze River Delta urban agglomerations should involve regional joint prevention and control as well as collaborative control of particulate matter and ozone. Moreover, measures such as rational planning of the spatial distribution of urban population, accelerating industrial structure adjustment and ecological transformation, optimizing energy structure, advocating green and low-carbon production and lifestyle should be adopted to effectively control air pollution and achieve ecological environmental protection and high-quality development of the Yangtze River Delta urban agglomeration.

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