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Research article

Spatiotemporal variation and influencing factors of air pollution in Anhui Province

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A R T I C L E I N F O

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A B S T R A C T

Anhui Province locates in the Yangtze River Delta region. The spatial difference between the north and the south is significant, and the air quality is improved over time. Studying the spatial and temporal changes of air pollution and its influencing factors for the coordinated control of air pollutants in the Yangtze River Delta region is significant. This study used the annual and monthly average data of six pollutants, $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO, in Anhui Province and various cities from 2015 to 2021 and analyzed the spatiotemporal change characteristics using Excel and GIS software. Meanwhile, this paper used the SPSS correlation analysis method to analyze the correlation between pollutants and meteorological factors and analyzed the impact of economic development and environmental protection policies. The results are shown below. (1) The concentrations of SO_2, NO_2, and CO showed an overall downward trend at an interannual level. Meanwhile, the concentrations of PM_{10} and $PM_{2.5}$ first increased slowly before 2017 and then declined, while the concentrations of O_3 increased significantly before 2018 and then declined slowly. On a monthly scale, O_3 presented an M-shaped change, while the other five pollutants basically presented a U-shaped change mode. The top monthly pollutants in each city followed the order of $PM_{2.5}$, O_3, PM_{10}, and NO_2. (2) $PM_{2.5}$ and PM_{10} showed apparent characteristics of high concentrations in the north and low concentrations in the south in space. There were no significant differences in NO_2, SO_2, and CO pollution between the north and the south in space, and the differences in spatial pollution among cities were reduced significantly. (3) Five pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO) except O_3 were positively correlated, and the degree of correlation was correlated, strongly correlated, and above. However, five pollutants were negatively correlated with O_3. The temperature had the most significant impact of negative correlation on five pollutants except for O_3. The sunshine duration had the most significant impact on O_3. (4) Economic growth and environmental protection policies in Anhui Province have positively affected environmental governance.

1. Introduction

Regional air pollution and socio-economic development are closely linked. The excessive emissions of air pollutants caused by human activities [1], connected with the influence of natural and meteorological factors, result in prominent air pollution in autumn and winter in most regions in China, with significant spatiotemporal differences [2]. Air pollution is a critical factor affecting economic

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development, especially in developed regions such as the Beijing-Tianjin-Hebei region, the Pearl River Delta, and the Yangtze River Delta [3,4], and is also one of the critical risk factors endangering public health [5]. At the same time, many scholars have studied the spatiotemporal variation and effects of air pollutant concentrations on the national, typical regional, provincial and urban scales [3, 6–8], and analyzed the spatiotemporal distribution of air pollution or air quality, as well as influencing factors using different models [9] with the help of specific analysis methods [10] and techniques [11]. However, most studies focused on the spatiotemporal variation of specific indicators such as $PM_{2.5}$, O_3, or AQI or pollutants in a city, and typical regions such as the Beijing-Tianjin-Hebei region, the Pearl River Delta, and the Yangtze River Delta. Some scholars have studied the spatiotemporal distribution of $PM_{2.5}$, CO, and O_3 pollution in Anhui Province [12,13]. However, the comprehensive analysis of the spatiotemporal pollution characteristics of $PM_{2.5}$, O_3, PM_{10}, NO_2, CO, and SO_2 has not has not yet to be reported in Anhui Province.

The air pollution in Anhui Province has a substantial spatial and temporal representation. It locates in the Yangtze River Delta region, and the spatial difference between the north and the south is significant. From 2015 to 2021, it experienced the connection between the "Ten Regulations of Air Pollution Prevention" and the "Blue Sky Protection Campaign." Air pollution and quality changed significantly, and time was also typical. Moreover, various air pollutants interact, resulting in complex pollution problems. A comprehensive analysis of the spatiotemporal changes and influencing factors of various pollutants could better demonstrate the effectiveness of comprehensive regional governance and air pollution control. Futhermore, it was necessary to study the spatiotemporal variation and influencing factors of air pollutant concentrations in Anhui Province from 2015 to 2021 and analyze the changing trend and the new pollution prevention and control situation. This study analyzed the spatiotemporal variation of air pollutants and their influencing factors in Anhui Province to provide primary data and a scientific basis for the subsequent prevention and control of air pollution.

Anhui Province has a substantial spatial and temporal representation of air pollution. It locates in the Yangtze River Delta, with a sizeable spatial difference between the north and the south. From 2015 to 2021, Anhui Province experienced the "Ten Regulations of Air Pollution Prevention" and the "Blue Sky Protection Campaign" in terms of time, with apparent changes in air pollution and quality, which was very typical of time and space. Moreover, various air pollutants interact, and there is a compound pollution problem. Comprehensive analysis of the spatiotemporal changes and influencing factors of various pollutants could better show the effectiveness of regional comprehensive treatment and air pollution control.

2. Materials and methods

2.1. Overview of the study area

Anhui Province is located in the Yangtze River Delta region, including 16 cities. Its terrain consists of the Huaibei Plain, the Jianghuai Hills, and the Southern Anhui Mountains from the north to the south. Due to the large span between the north and the south, which is divided into two parts by the Yangtze River and the Huaihe River, there are significant differences in geographical spatial

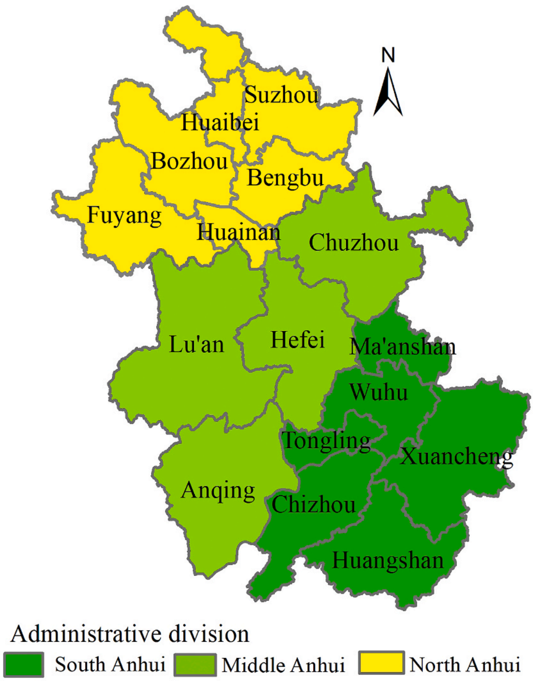

Fig. 1. Regional division of Anhui Province.

characteristics and climate. The regional division of Anhui Province is shown in Fig. 1.

2.2. Data source and processing

The annual and monthly mean values of the six air pollutants in Anhui Province and various cities were from the annual and monthly environmental quality reports regularly published by the Anhui Provincial Department of Ecology and Environment. Meteorological data of Anhui Province and various cities were from the Anhui Provincial Public Meteorological Service Center and Anhui Statistical Yearbook. The economic data of Anhui Province were from annual statistical reports published by the Anhui Provincial Bureau of Statistics.

2.3. Research methods

2.3.1. Classification of pollution levels

According to five intervals, this paper classified the concentrations of each pollutant to analyze spatial distribution characteristics [14]. Meanwhile, the concentration range of each interval was determined based on the current situation of pollutant concentrations on statistical time scales and the Ambient Air Quality Standards (GB3095-2012). The primary standard was the cut-off point of low-medium concentration, and the secondary standard was the cut-off point of near-high concentration for $PM_{2.5}$, PM_{10}, and O_3. Since the concentrations of SO_2 did not substantially exceed the secondary level on statistical time scales, the primary concentration could be the cut-off point of near-high concentration. Primary and secondary concentrations were the same for NO_2 and CO. According to the concentrations on statistical time scales, primary concentration was the cut-off point of high concentration for NO_2. However, primary concentration was the upper limit of high concentration for CO due to its low actual concentrations (Table 1).

2.3.2. SPSS correlation coefficient analysis

This paper applied Excel and SPSS17.0 to process relevant data. Pearson Correlation Analysis and Spearman Correlation Analysis were used to determining the correlation between atmospheric pollutants and the correlation between pollutants and meteorological factors.

2.3.3. Spatial analysis

This paper obtained the annual mean and percentile concentrations of air pollutants in 16 cities of Anhui Province from 2015 to 2021. According to the concentration ranges in Table 1, the ArcGIS 10.7 software was used to express the spatial pollution of each pollutant in a visual form. In the meantime, the spatial pattern and differentiation of air pollution in each city in the past seven years were analyzed.

3. Results and discussion

3.1. Temporal variation characteristics of atmospheric pollutants

3.1.1. Interannual variation characteristics of atmospheric pollutant concentrations

As shown in Fig. 2, the concentrations of SO_2 and CO showed an overall downward trend. Wherein the annual mean concentration of SO_2 had the most significant decrease, from 22 $\mu g/m^3$ to 8 $\mu g/m^3$. In particular, the annual mean concentrations after 2018 were much lower than the primary standard. Therefore, the future reduction trend tended to be critical. The concentrations of NO_2 increased before 2017 and then slowly dropped to 26 $\mu g/m^3$. According to research results, the concentrations of NO_2 and CO were both lower than the primary standard. The concentrations of PM_{10} and $PM_{2.5}$ first increased slowly before 2017. After then, both had a significant downward trend, from 80 $\mu g/m^3$ and 55 $\mu g/m^3$ in 2015 to 61 $\mu g/m^3$ and 35 $\mu g/m^3$ in 2021. However, the concentrations of O_3 had been increasing significantly before 2018, reaching a maximum value of 166 $\mu g/m^3$ (exceeding the secondary standard). Then, it slowly dropped to 148 $\mu g/m^3$ (below the secondary standard), remaining at a high level. After concluding the interannual variation of various pollutants, the emission reduction of air pollutants in Anhui Province, except O_3, was significant in the statistical years, especially for SO_2, NO_2, and particulate matter after 2018. This finding indicated that the strategy of the Blue-Sky Defense War and various pollution control measures achieved significant effects on air pollution control.

Table 1
Concentration ranges of six pollutants.

Intervals	$PM_{2.5}$	PM_{10}	O_3	SO_2	NO_2	CO
Low concentration	≤15	≤40	≤100	≤10	≤10	≤1
Low-medium concentration	15 < Ci ≤ 25	40 < Ci ≤ 55	100 < Ci ≤ 130	10 < Ci ≤ 15	10 < Ci ≤ 20	1 < Ci ≤ 1.5
Medium-high concentration	25 < Ci ≤ 35	55 < Ci ≤ 70	130 < Ci ≤ 160	15 < Ci ≤ 20	20 < Ci ≤ 30	1.5 < Ci ≤ 2.0
Near high concentration	35 < Ci ≤ 45	70 < Ci ≤ 85	160 < Ci ≤ 180	20 < Ci ≤ 25	30 < Ci ≤ 40	2.0 < Ci ≤ 2.5
High concentration	>45	>85	>180	>25	>40	2.5 < Ci ≤ 4.0
Primary concentration limit	15	40	100①	20	40	4②
Secondary concentration limit	35	70	160①	60	40	4②

Notes: CO and O_3 were counted through percentile concentrations, and other pollutants were counted through annual mean concentrations.

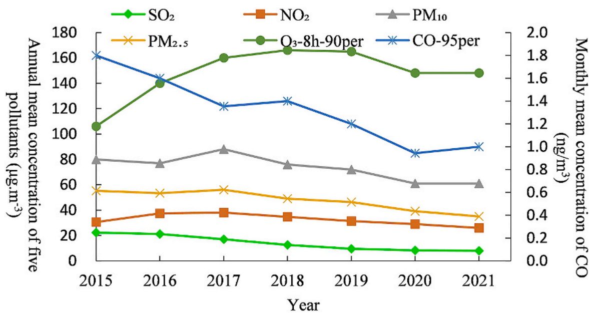

Fig. 2. Interannual variation of air pollutant concentrations in Anhui Province from 2015 to 2021.

3.1.2. Monthly variation characteristics of atmospheric pollutant concentrations

According to the monthly mean concentrations of six atmospheric pollutants in Anhui Province from 2015 to 2021, researchers plotted the monthly variation curves of six pollutants, as shown in Fig. 3.

As shown in Fig. 3, the concentrations of four pollutants (NO_2, PM_{10}, $PM_{2.5}$, and CO) showed a U-shaped change law in the months of a year. Meanwhile, the concentrations of SO_2 exhibited a minor U-shaped change. All pollutants reached low concentrations from June to August. July was the high-incidence period of the lowest concentrations in a year, and higher concentrations often occurred in December, January, and February. The pollution in winter was significantly higher than in summer, resulting from high temperatures in summer and the negative correlation between temperature and pollutants. As a concentrated rainfall period, summer rainwater could have a scouring effect on pollutants. In winter, increased use of fossil fuels, dry climate, and the Spring Festival effect could aggravate pollution. For example, the period with the most serious PM_{10} and $PM_{2.5}$ pollution was December, except January 2019. The concentrations of PM_{10} and NO_2 reached small peaks in March and April each year. On the other hand, the monthly variation of O_3 showed an opposite trend to other pollutants. In detail, the monthly mean concentrations showed an M-shaped bimodal change law. The concentrations of O_3 presented an irregular M shape before 2019, followed by a regular M shape. The overall variation was characterized by an increase followed by a decrease, with high concentrations in May and September and minimum concentrations in January or December. High concentrations had the most frequent occurrence rate in May when pollution reached the most serious. By comparison, minimum concentrations occurred most frequently in December when pollution was lightest. Furthermore, there is a certain temporal difference between the monthly peaks and valleys of various pollutants in this study and the others. For example, the lowest concentration of O_3 in Beijing and Shandong occurred in August [15,16]. The monthly O_3 variation showed an inverted V-shaped unimodal variation in some regions, while the double-peak in some regions were different [17,18]. According to the research result, the monthly concentration structure changes of pollutants in different regions were related to locations, meteorological conditions, chemical reactions, topographic characteristics, and natural environment [19–21]. Due to different latitudes, O_3 had significant north-south differences under temperature, light, rainfall, and other factors on different dimensions. In the monthly variation, Shenyang, Beijing, and other places presented a single-peak type, Hefei, Nanjing, and other places presented a double-peak type, and Guangzhou presented a weak three-peak [17]. However, the differences among the peak type in concentration were also related to the differences in the rainy period [22].

3.1.3. Analysis of the monthly pollution frequencies of air pollutants in various cities

After counting the monthly pollution status of 16 cities in Anhui Province from 2015 to 2021, the monthly pollution calendar was made based on the major pollutants with the maximal pollution index in each city for the month, as shown in Fig. 4. The major air pollutants in each city were $PM_{2.5}$, O_3, PM_{10}, and NO_2, without CO and SO_2 pollution. $PM_{2.5}$ was the most frequent and major pollutant in 2015 and 2016. After that, $PM_{2.5}$ was the pollutant with the highest frequency in each city from November–December to January–March of the following year in 2017–2020. However, the frequency of $PM_{2.5}$ as the major pollutant had a significant

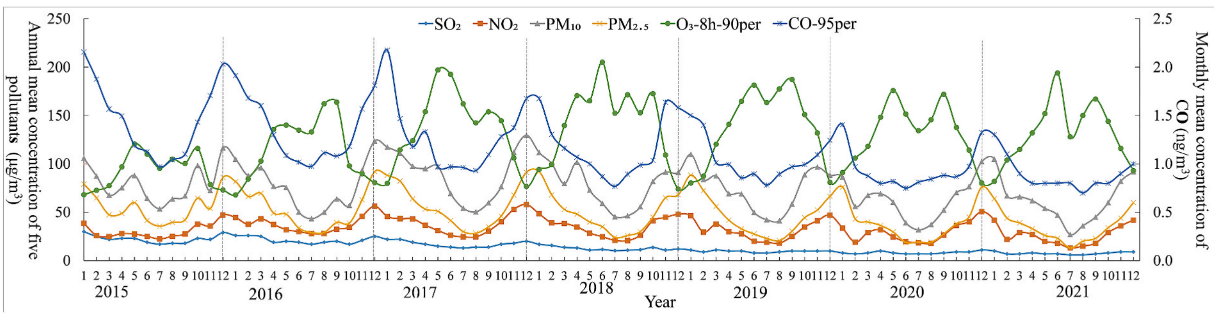

Fig. 3. Monthly variation of air pollutant concentrations in Anhui Province from 2015 to 2021.

reduction in 2021 with the increasing frequency of O_3 and PM_{10}. O_3, the second major pollutant, expanded from August 2016 to June–September in 2017 and 2018. Then, the O_3 had a significant growing trend in polluted areas and periods from May to September 2019–2021. In 2021, O_3 surpassed $PM_{2.5}$ and became the most frequent pollutant, especially in southern Anhui, with relatively good air quality. In the meantime, the O_3 pollution in Huangshan was the most prominent. PM_{10} was the third major pollutant, followed closely by a frequency lower than $PM_{2.5}$ and O_3. In 2021, the PM_{10} had a significant increase, especially in 6 northern cities and Hefei and Lu'an in central Anhui, with the main distribution in March–May. Therefore, preventing and controlling PM_{10} pollution should be emphasized. By comparison, NO_2 had a lower frequency as a major pollutant, mainly in Tongling, Wuhu, Hefei, and Ma'anshan, in October and November. In the future, major pollutants for the prevention and control of air pollution in Anhui cities are particulate matter and O_3, especially O_3 and its composite pollution.

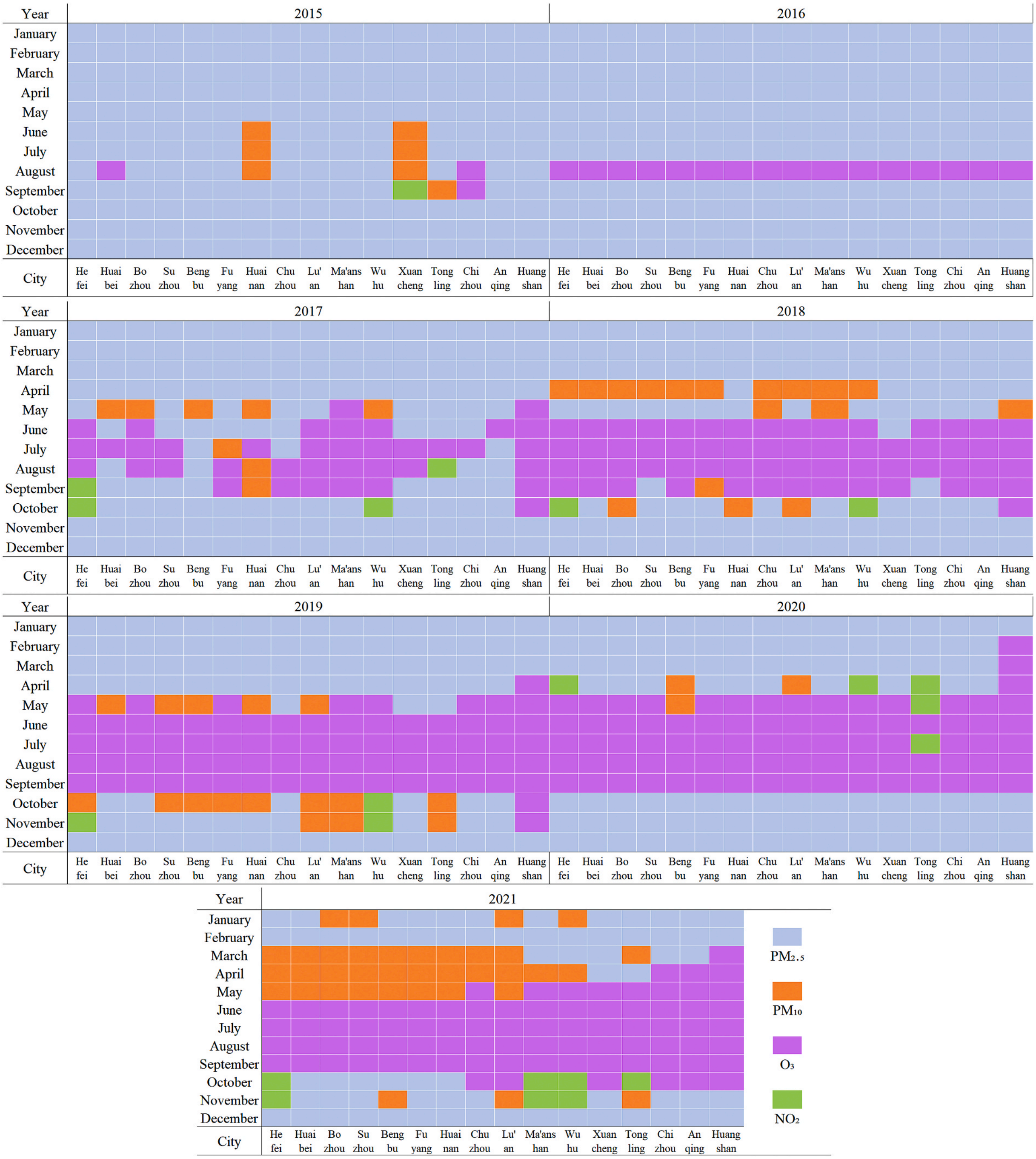

Fig. 4. Monthly calendar of major pollutants in each city from 2015 to 2021.

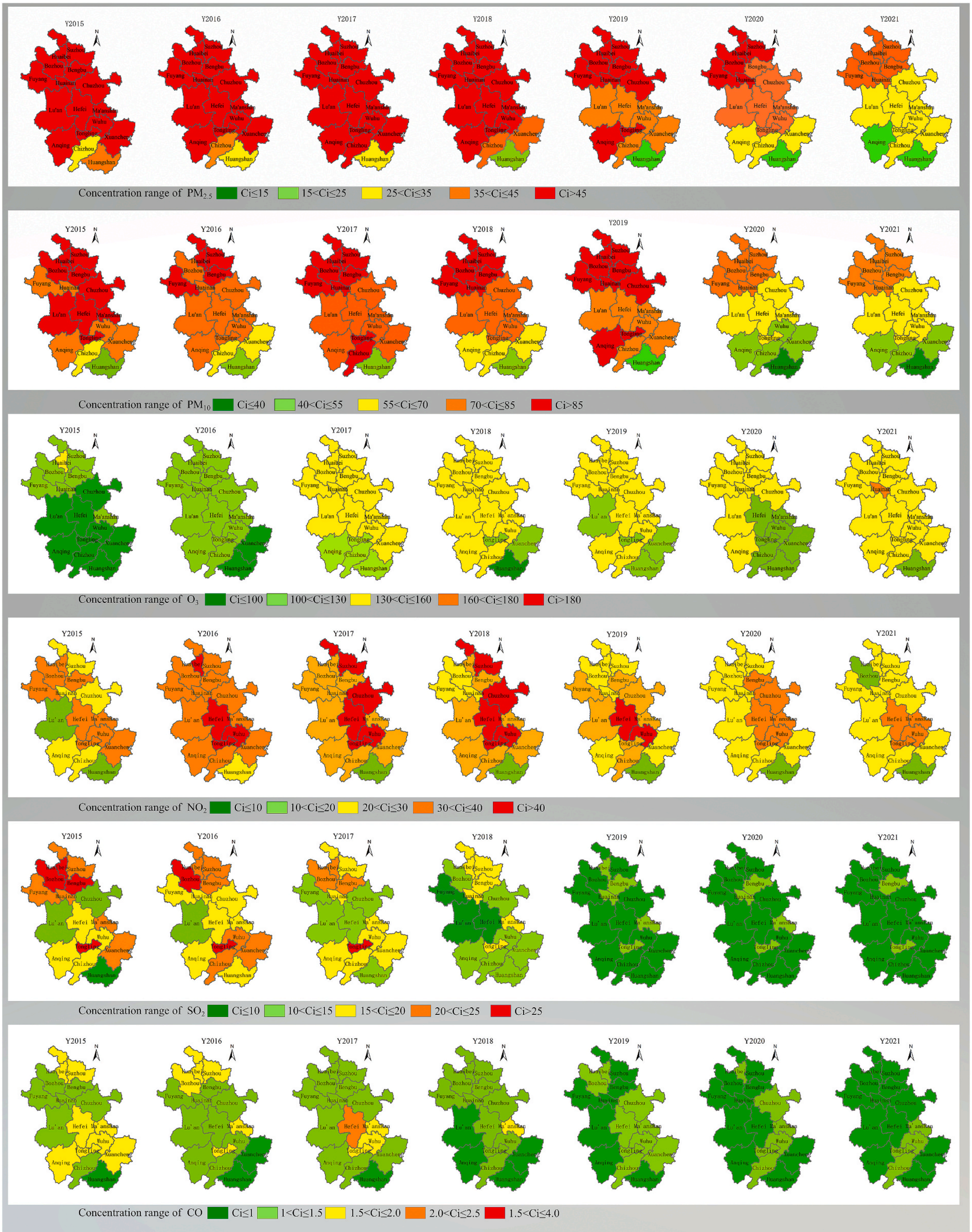

Fig. 5. Spatial distribution of the concentrations of the six pollutants from 2015 to 2021.

3.2. Analysis of spatial variation of atmospheric pollutant concentrations

According to the classification in Table 1, the spatial distribution of $PM_{2.5}$, PM_{10}, O_3, NO_2, SO_2, and CO in each city in Anhui Province from 2015 to 2021 was plotted (Fig. 5).

According to Fig. 5, $PM_{2.5}$ and PM_{10} changed from high concentrations in northern Anhui to medium and low concentrations in central and southern Anhui. Except for Chizhou and Huangshan, other cities showed high pollution levels before 2019. Although the spatial pollution gradually improved, the pollution in northern Anhui was still severe. The annual mean concentration in six northern cities still exceeded 35 $\mu g/m^3$ in 2021. Except for Tongling in 2015 and Chizhou in 2018, high-concentration PM_{10} pollution frequently happened in northern cities. Meanwhile, the concentrations of PM_{10} in central Anhui gradually decreased from a high concentration to below the secondary concentration. After 2019, the concentrations of PM_{10} in Huangshan remained at the best level, below the primary concentration. The significant difference in particulate pollutants between the north and the south was related to the large span, climate, geography, urban development, and energy structure. Compared with the hilly and mountainous topography and subtropical monsoon climate in southern Anhui, the Huaihe Plain and temperate monsoon climate in northern Anhui had a driving impact on the transmission and transportation of particulate matter. The dry climate and the impact of dust weather in winter could easily lead to particulate matter pollution in northern Anhui. Furthermore, plain areas were conducive to the diffusion of pollutants. The transmission effect of wind can aggravate the input pollution of particulate matter [23,24], leading to high concentrations of $PM_{2.5}$ and PM_{10} in northern cities as well as minor differences in spatial pollution among northern Anhui cities. In addition, the industrial quantity of coal as the main energy source in northern Anhui is higher than in southern Anhui, causing the large emission of particulate pollutants and exacerbating the particulate pollution in northern Anhui.

With the expansion of the O_3 pollution in space, the O_3 pollution might be more and more serious. Except for Huangshan, the O_3 pollution exceeded 130 $\mu g/m^3$ in other cities in 2021, with concentrations in Huainan exceeding the secondary concentration limit. The concentrations in Chuzhou and Ma'anshan were as high as 159 $\mu g/m^3$. What is more, the concentrations in Huaibei, Bozhou, Wuhu, and Chizhou exceeded 150 $\mu g/m^3$, and the pollution level in northern Anhui higher than in central and southern parts. NO_2, SO_2, and CO pollution showed no significant difference between the north and the south, but showed an obvious downward trend in the time dimension. NO_2 showed an obvious increasing trend first and then decreased, reaching the worst level in 2017. After that, the pollution trend was significantly moderated. After 2020, the concentrations of NO_2 in all cities were lower than 40 $\mu g/m^3$. The fast urban and industrial development could greatly influence fossil fuel combustion, cement production, and automobile exhaust emissions [25]. As a precursor to the formation of $PM_{2.5}$ and O_3, NO_2 had a direct impact on air quality, which needed important attention. The pollution of SO_2 and CO was the lightest, exceeding the secondary concentration limit in the statistical years. The concentrations of SO_2 were slightly significant in Tongling, followed by Bozhou, Huaibei, and Bengbu in northern Anhui. The SO_2 emission had a significant reduction in all cities. After 2018, the concentrations of SO_2 were lower than the primary level (20 $\mu g/m^3$). The concentrations of CO in all cities were below the primary concentration limit. Compared with other regions, Hefei in central Anhui and along the Yangtze River had higher concentrations. During the rapid urbanization process of Hefei in recent years, the traffic and industrial emissions had more impact on the air quality than other factors. Along the Yangtze River, ondustrial cities such as Tongling and Maanshan had steel bases, chemical enterprises, and oil refineries with high CO emissions. In the meantime, the near-surface CO was more susceptible to local emissions, vertical transmission, and other factors [12,26]. In summary, the difference in air pollutant concentrations between cities in Anhui has significantly reduced until 2021, indicating the significant promotion of the atmospheric environment.

3.3. Influencing factors and correlation analysis

3.3.1. Correlation analysis between pollutants

Researchers used SPSS to conduct the Pearson Correlation Analysis between the monthly mean concentrations of air pollutants in Anhui Province from 2015 to 2021. (the results are shown in Table 2). According to the interval division of correlation coefficients at 0.01 and 0.05 [27], the correlations between any two pollutants (including SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO) all showed positive and strong correlations and above. The correlation coefficients between pollutants (except SO_2 and NO_2) were all above 0.5, indicating synergy between pollutants. The strong correlation between PM_{10} and $PM_{2.5}$ ($r = 0.942$) showed a strong synergy in particulate matter emissions with the same emission source and different particle sizes [28]. PM_{10}, $PM_{2.5}$, and NO_2 were strongly correlated ($r > 0.8$), indicating synergy between changes in the concentrations of PM_{10}, $PM_{2.5}$, and NO_2. Meanwhile, increasing NO_2 concentration would

Table 2
Correlation analysis of six air pollutants in Anhui Province.

Pollutant	SO_2	NO_2	PM_{10}	$PM_{2.5}$	CO	O_3
SO_2	1	0.470**	0.534**	0.581**	0.774**	−0.475**
NO_2		1	0.895**	0.859**	0.683**	−0.565**
PM_{10}			1	0.942**	0.758**	−0.570**
$PM_{2.5}$				1	0.859**	−0.736**
CO					1	−0.723**
O_3						1

Notes: ** indicates significant correlation at level 0.01 (double-tailed); N = 84.

Table 3
Correlation analysis of six air pollutants and meteorological factors in Anhui Province and its cities.

City	Meteorologicalfactor	SO_2	NO_2	PM_{10}	$PM_{2.5}$	CO	O_3	City	Meteorologicalfactor	SO_2	NO_2	PM_{10}	$PM_{2.5}$	CO	O_3
Bozhou	Temperature	−0.294*	−0.682**	−0.817**	−0.874**	−0.625**	0.752**	Lu'an	Temperature	−0.21	−0.547**	−0.746**	−0.825**	−0.774**	0.633**
	Wind speed	−0.141	−0.266*	0.052	0.013	−0.136	0.048		Wind speed	0.232	−0.074	−0.005	−0.022	0.061	−0.046
	Rainfall	−0.172	−0.469**	−0.532**	−0.473**	−0.292*	0.236*		Rainfall	−0.039	−0.355**	−0.565**	−0.463**	−0.342**	0.22
	Sunshine duration	−0.283*	−0.514**	−0.511**	−0.658**	−0.544**	0.679**		Sunshine duration	−0.325*	−0.346**	−0.460**	−0.596**	−0.562**	0.550**
Huaibei	Temperature	−0.423**	−0.830**	−0.812**	−0.885**	−0.676**	0.850**	Anqing	Temperature	−0.250*	−0.668**	−0.723**	−0.834**	−0.526**	0.521**
	Wind speed	−0.379**	−0.241*	0.003	−0.066	−0.285*	0.096		Wind speed	0.616**	0.081	0.238*	0.151	0.304**	−0.313**
	Rainfall	−0.300*	−0.489**	−0.577**	−0.468**	−0.342**	0.311**		Rainfall	−0.031	−0.294*	−0.505**	−0.457**	−0.236*	0.053
	Sunshine duration	−0.288*	−0.609**	−0.409**	−0.614**	−0.555**	0.750**		Sunshine duration	−0.209	−0.436**	−0.400**	−0.531**	−0.349**	0.482**
Suzhou	Temperature	−0.346**	−0.607**	−0.796**	−0.799**	−0.670**	0.652**	Ma'anshan	Temperature	−0.486**	−0.810**	−0.700**	−0.842**	−0.606**	0.881**
	Wind speed	−0.075	−0.113	0.001	−0.085	−0.271*	0.189		Wind speed	0.17	−0.265*	−0.059	−0.092	−0.015	0.201
	Rainfall	−0.2	−0.249*	−0.535**	−0.424**	−0.265*	0.253*		Rainfall	−0.252*	−0.482**	−0.481**	−0.385**	−0.249*	0.265*
	Sunshine duration	−0.18	−0.360**	−0.427**	−0.502**	−0.595**	0.612**		Sunshine duration	−0.262*	−0.475**	−0.338**	−0.547**	−0.515**	0.685**
Fuyang	Temperature	−0.400**	−0.601**	−0.785**	−0.887**	−0.727**	0.770**	Tongling	Temperature	−0.237*	−0.677**	−0.757**	−0.823**	−0.651**	0.796**
	Wind speed	0.008	−0.23	0.048	0.025	−0.069	−0.044		Wind speed	0.378**	−0.007	0.019	0.081	0.207	−0.065
	Rainfall	−0.287*	−0.523**	−0.553**	−0.542**	−0.404**	0.380**		Rainfall	0.074	−0.389**	−0.499**	−0.416**	−0.221	0.105
	Sunshine duration	−0.326*	−0.419**	−0.444**	−0.579**	−0.645**	0.655**		Sunshine duration	−0.172	−0.408**	−0.431**	−0.558**	−0.435**	0.711**
Huainan	Temperature	−0.436**	−0.750**	−0.773**	−0.907**	−0.682**	0.740**	Wuhu	Temperature	−0.310**	−0.614**	−0.652**	−0.822**	−0.629**	0.616**
	Wind speed	0.179	0.032	0.179	0.245*	0.107	−0.109		Wind speed	0.276*	−0.132	0.108	0.036	0.215	−0.061
	Rainfall	−0.288*	−0.461**	−0.472**	−0.445**	−0.311**	0.298*		Rainfall	−0.131	−0.423**	−0.480**	−0.415**	−0.304**	0.059
	Sunshine duration	−0.350**	−0.547**	−0.440**	−0.598**	−0.556**	0.695**		Sunshine duration	−0.142	−0.418**	−0.404**	−0.610**	−0.481**	0.534**
Bengbu	Temperature	−0.339**	−0.681**	−0.792**	−0.870**	−0.762**	0.768**	Chizhou	Temperature	−0.289*	−0.718**	−0.723**	−0.779**	−0.763**	0.740**
	Wind speed	0.009	−0.157	0.073	0.057	0.054	−0.024		Wind speed	−0.018	−0.028	−0.06	−0.057	−0.124	0.069
	Rainfall	−0.246*	−0.463**	−0.562**	−0.460**	−0.376**	0.342**		Rainfall	−0.011	−0.383**	−0.455**	−0.408**	−0.282*	0.126
	Sunshine duration	−0.237	−0.450**	−0.416**	−0.616**	−0.588**	0.703**		Sunshine duration	−0.267*	−0.481**	−0.442**	−0.516**	−0.587**	0.685**
Hefei	Temperature	−0.420**	−0.560**	−0.542**	−0.794**	−0.651**	0.790**	Huangshan	Temperature	0.218	−0.729**	−0.724**	−0.778**	−0.410**	0.212
	Wind speed	−0.031	−0.296*	−0.11	−0.119	−0.186	0.05		Wind speed	0.139	−0.129	0.001	−0.028	−0.141	−0.237*
	Rainfall	−0.245*	−0.424**	−0.499**	−0.404**	−0.284*	0.175		Rainfall	0.042	−0.383**	−0.473**	−0.352**	−0.21	−0.132
	Sunshine duration	−0.290*	−0.311*	−0.211	−0.561**	−0.561**	0.682**		Sunshine duration	0.116	−0.457**	−0.144	−0.269*	−0.256*	0.426**
Chuzhou	Temperature	−0.166	−0.689**	−0.756**	−0.817**	−0.779**	0.614**	Xuancheng	Temperature	−0.237*	−0.729**	−0.648**	−0.832**	−0.597**	0.520**
	Wind speed	−0.012	−0.086	0.071	0.096	0.134	−0.046		Wind speed	0.445**	−0.184	0.109	0.014	0.072	−0.117
	Rainfall	−0.053	−0.369**	−0.481**	−0.393**	−0.381**	0.173		Rainfall	0.015	−0.272*	−0.407**	−0.335**	−0.234*	−0.17
	Sunshine duration	−0.159	−0.392**	−0.360**	−0.544**	−0.520**	0.534**		Sunshine duration	−0.171	−0.605**	−0.375**	−0.536**	−0.495**	0.502**
Anhui	Temperature	−0.334**	−0.759**	−0.810**	−0.871**	−0.763**	0.766**	Anhui	Rainfall	−0.153	−0.516**	−0.607**	−0.513**	−0.389**	0.236*
	Wind speed	0.213	−0.11	0.041	0.029	0.082	−0.03		Sunshine duration	−0.205	−0.468**	−0.401**	−0.542**	−0.542**	0.672**

Notes: ** indicates significant correlation at level 0.01 (double-tailed); * indicates significant correlation at level 0.05 (double-tailed); N = 72.

aggravate the pollution of particulate matter. A study showed that controlling NO_2 could be beneficial for further reducing $PM_{2.5}$ pollution [29]. The correlations between $PM_{2.5}$ and PM10 and CO were as follows: strong correlation ($r = 0.859$) and strong correlation ($r = 0.7580$), possibly resulting from the same emission source of vehicle exhaust emissions and fossil fuel combustion [6]. All pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, and CO) had a negative correlation with O_3, especially $PM_{2.5}$. Based on this finding, researchers concluded that a higher concentration of $PM_{2.5}$ would inhibit the secondary generation of O_3 [30]. The continuous emission reduction measures in Anhui significantly decreased the $PM_{2.5}$ concentration, but the inhibitory effect on increasing O_3 concentration tended to weaken. The increasing O_3 pollution in Anhui Province became a new environmental issue caused by the remarkable achievements in controlling $PM_{2.5}$ and other pollutants. In the future, coordinated control should be carried out based on the formation mechanism of $PM_{2.5}$ and O_3.

3.3.2. Influence of meteorological factors on air pollution

Table 3 shows the Pearson Correlation Analysis results of meteorological data in Anhui and its cities from 2015 to 2020, such as the monthly mean values of temperature, wind speed, sunshine duration, and rainfall (not fully published by each city in 2021), and the monthly mean values of six pollutants at the corresponding time.

In Table 3, the temperature has the greatest negative correlation with pollutants (except for O_3) among the four meteorological factors. In particular, the temperature achieved an extremely strong correlation with $PM_{2.5}$ and a strong correlation with PM_{10} in each city, with the greatest impact on $PM_{2.5}$. Meanwhile, the temperature had a more significant impact on northern Anhui than other regions., The correlation with overall $PM_{2.5}$ and PM_{10} in Anhui was 0.871 and 0.810, an extremely strong and negative correlation. Furthermore, the temperature had a strong correlation with NO_2 and CO, without significant differences between cities. The temperature had a correlation with SO_2 and a weak correlation with pollutants in Anhui. Except for Huangshan (without correlation), Anqing, and Xuancheng (with correlation), the temperature had a strong positive correlation with the O_3 in other cities. The higher the temperature was, the higher the O_3 concentration was. The correlation effect of wind speed on pollutants in Anhui was not significant. In some cities, wind speed had a negative correlation with SO_2, NO_2, or CO, but no correlation between wind speed and PM_{10}, $PM_{2.5}$, and O_3. This phenomenon indicated that the pollutant concentration would decrease with increasing wind speed.

Although no correlation was between overall rainfall in Anhui and SO_2, a weak negative correlation still existed between rainfall and SO_2 in some cities. Overall rainfall had a negative correlation with NO_2, a strong correlation with PM_{10}, a correlation with $PM_{2.5}$, and a weak negative correlation with CO. Rainfall had a strong correlation with pollutants in each city and a weak correlation with a few pollutants, indicating that rainfall had a removal effect on most atmospheric pollutants. There was a weak positive correlation between rainfall and O_3 in Anhui Province, with a certain spatial difference. Meanwhile, there was a weak positive correlation between rainfall and O_3 in northern Anhui. Except for Ma'anshan, no correlation was between rainfall and O_3 in central and southern cities. The sunshine duration had the greatest impact on O_3, showing a strong positive correlation with a certain spatial difference. A strong correlation between sunshine duration and O_3 was found in six northern cities, indicating that dry and sunny weather would easily stimulate the O_3 pollution. In summary, there was no correlation between sunshine duration and SO_2. By comparison, the sunshine duration had a negative correlation with NO_2, PM_{10}, and $PM_{2.5}$. Wherein the correlation between sunshine duration and $PM_{2.5}$ was more significant, indicating that solar radiation had opposite effects on O_3 and $PM_{2.5}$.

3.3.3. Impact of economic factors on air pollution

Many anthropogenic and economic factors can influence air pollution, including industrial production, transportation, energy consumption, etc. The GDP and industrial GDP of Anhui increased from 2383.118 billion yuan and 836.056 billion yuan in 2015–4295.918 billion yuan and 1308.169 billion yuan in 2021, showing a significant increase. The concentrations of various pollutants (except O_3) had a significant decrease in 2021, indicating that pollutant emissions weakened with economic development. The pollutant concentration decreased with economic growth after 2018, indicating that increasing economic benefits in Anhui had a positive effect on environmental governance. The economic and urban developmentt could better promote industrial agglomeration, the management and technological innovation of the environmental protection industry, the green development of enterprises, and the energy consumption reduction of the per unit GDP, which was conducive to the emission reduction of air pollutants and the air quality promotion. However, Anhui still faced great environmental pressure during economic growth. The energy consumption of per unit of industrial value-added in Anhui from 2015 to 2021 was 0.88, 0.90, 0.97, 1.14, 1.23, 1.22, and 1.16t standard coal per 10,000 yuan. Although the energy consumption has been eased since 2019, the level is still high. The industrial-based cities in the northern part and along the Yangtze River still faced great pressure to reduce emissions aroused by the industrial growth. For Anhui, more efforts should be made in the energy consumption of industrial added value. The ratio of NO_2 and SO_2 from 2015 to 2021 was 1.37, 1.77, 2.23, 2.75, 3.28, 3.49, and 3.25, showing an obvious upward trend. This finding also indicated that motor vehicles contributed more and more NO_2 pollution with an increasing trend of private vehicles. NO_2 contributed greatly to the co-pollution with other pollutants, especially $PM_{2.5}$ and O_3. The NO_2 pollution needs to be focused on, especially traffic pollution.

3.3.4. Impact of environmental protection policies on air pollution

From 2015 to 2021, the air quality in Anhui experienced two stages, a decline (2015–2017) and a significant improvement (2018–2021). In the meantime, air pollution prevention and control policies also showed obvious time characteristics. Although the emphasis on the responsibility of local governments promoted the atmospheric environment quality in the declining stage, targeting and implementing specific measures was ignored. Therefore, quality improvement policies did not achieve strong practical results in the short term. In the next stage, the Blue-Sky Defense War was the top priority. The relevant policies subsequently to improve the atmospheric environment quality in Anhui were of great significance, such as the Implementation Plan of Three-Year Action Plan for

Winning the Blue-Sky Defense War in Anhui Province and the Announcement of Implementing the Special Emission Limits of Air Pollutants in Key Control Areas in Anhui Province. Various cities also introduced corresponding prevention and control measures, leading to a significant air quality promotion. During this period, not only the main responsibility of governments was strengthened, but the emission reduction measures were more targeted and feasible. Under the active intervention of governments, environmental protection policies in industry and transportation were successively issued, such as the Anhui Provincial Prevention and Control Measures of Motor Vehicle Exhaust Pollution, the Anhui Provincial Air Pollutant Emission Standards in Cement Industry, etc. Meanwhile, government departments also paid attention to treating volatile organic compounds. For example, policies such as the Notice on Comprehensively Promoting the Comprehensive Treatment of Volatile Organic Compounds and the 100-day Action Plan for the Pollution Control of Volatile Organic Compounds in the Summer of 2020, were introduced. The effectiveness of air pollution prevention and control became more and more significant than the first stage. Environment protection policies played a positive role in promoting the participation of all parties in environmental governance through pressure and incentive effects, reducing the emissions of pollutants except O_3. Under the new circumstance, the coordinated control of O_3 and other pollutants should be emphasized. Furthermore, the 14th Five-Year Plan emphasized promoting the *trans*-regional prevention and control of air pollution and low-carbon emission reduction. At the beginning of the 14th Five-Year Plan, the regional ecological environment protection standards, Emission Standards of Air Pollutants in the Pharmaceutical Industry, were issued in Anhui Province and other regions in the Yangtze River Delta, which was the first mandatory standard for ecological environment protection in the region. It was a concrete practice of establishing regional standard integration, which was of great significance for the coordinated control of $PM_{2.5}$ and O_3 in the Yangtze River Delta. In the future, governments should pay more attention to regional pollution prevention and control in Anhui. Through measures, such as benchmarking provinces and cities around the Yangtze River Delta, strengthening green and low-carbon transformation and development, and further optimizing and adjusting industrial energy and transportation structure, the air pollution prevention and control level can be further improved.

4. Conclusions

(1) At the interannual level, the concentrations of SO_2 and CO showed an overall downward trend among the six pollutants. The concentrations of NO_2, PM_{10}, and $PM_{2.5}$ first increased and then declined, while the concentrations of O_3 increased significantly before 2018 and then declined slowly. Meanwhile, at the monthly level, the concentrations of five pollutants (NO_2, PM_{10}, $PM_{2.5}$, CO, and SO_2) showed a U-shaped change law. The monthly mean concentrations of O_3 showed an M-shaped bimodal variation. $PM_{2.5}$, O_3, PM_{10}, and NO_2 were the significant pollutants in the monthly pollution calendar of each city, and $PM_{2.5}$ was the most frequent pollutant. Meanwhile, O_3 was the second major pollutant.
(2) $PM_{2.5}$ and PM_{10} showed significant characteristics of high concentrations in the north and low concentrations in the south in space. O_3 pollution has been expanding yearly in both time and space. The pollution situation in northern Anhui still needed to be solved. However, NO_2, SO_2, and CO pollution showed no significant difference between the north and the south in space but showed a significant downward trend in time. The difference in air pollutant concentrations among cities in Anhui Province have been significantly reduced in 2021.
(3) The correlation coefficients of other pollutants were all above 0.5, and there was strong synergy among all pollutants except for SO_2 and NO_2. Meanwhile, the temperature had the most significant impact of negative correlation on pollutants except for O_3. The correlation effect of wind speed on each pollutant was not significant. However, there was a correlation between rainfall and particulate matter, but not on other pollutants. The sunshine duration significantly impacted O3, showing a strong positive correlation with a particular spatial difference.
(4) The increased economic benefits of Anhui Province have had a positive effect on environmental governance. While emphasizing the primary responsibility of local governments, increasingly targeted and feasible emission reduction measures have been adopted in Anhui Province, which has played a positive role in promoting the participation of all parties in environmental governance. At last, the coordinated management of $PM_{2.5}$, PM_{10}, O_3, and NO_2 would be the focus of air pollution prevention and control policies in Anhui Province in the coming period.

Author contribution statement

Li Jia: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Jianping Sun: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Yanfang Fu: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

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