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Study on the Trend of Atmospheric Air Quality Changes, Pollution Characteristics and Causes in the Chengdu-Chongqing Region in China

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Abstract: *Based on the air pollutant spatial and temporal data of 16 major cities in the Chengdu-Chongqing region from 2015-2021, using the analysis methods of the spatial autocorrelation model and the characteristic radar chart, this paper analyzes the spatial and temporal characteristics of air pollution in the Chengdu-Chongqing region and the main sources and causes of air pollutants in different cities. The research results show: (1) temporally, the overall air quality in the Chengdu-Chongqing region shows an improving trend from 2015 to 2021, but the pollution is more serious in winter, and the air pollutants fine particulate matter($PM_{2.5}$) and sulfur dioxide(SO_2) pollution are prominent. (2) Spatially, the spatial distribution pattern of pollutants $PM_{2.5}$, inhalable particles (PM_{10}), nitrogen dioxide(NO_2) and SO_2 in Chengdu-Chongqing region shows the distribution characteristics of high in the west and low in the east, while pollutant carbon monoxide(CO) shows the characteristics of high in the east and low in the west. (3) In 2021, the air quality index (AQI index) of cities in Chengdu-Chongqing region show the spatial clustering characteristics of "high - high" and "low - low". (4) The urban air pollution in Chengdu-Chongqing region mainly includes four types: secondary-biased, coal-fired, motor vehicle-biased and dust-biased, among which, coal-fired is the main type of air pollution in Chengdu-Chongqing region.The findings of the study can provide decision support for targeted treatment of air pollution and high-quality economic and social development in the Chengdu-Chongqing region.*

Keywords: *Chengdu-Chongqing region; AQI index; air pollution; spatial and temporal characteristics*

1. Introduction

Chengdu-Chongqing region is an important region in western China. In the early stage, large industrial bases including military industry, metallurgy, chemical industry and petroleum were built [1]. Following rapid economic development, the Chengdu-Chongqing region has become the fourth pole of China's economic growth and it is the most densely populated region with the highest level of development and great development potential in western China [2]. However, while industrialization has achieved remarkable results, environmental pollution in the Chengdu-Chongqing region has become increasingly prominent, especially air pollution, which has become one of the top five regions of air pollution in China after Beijing-Tianjin-Hebei region [3,4].

Atmospheric pollution can pose a risk to public health and safety [5-7]. Some studies have shown that fine particulate matter ($PM_{2.5}$), inhalable particles (PM_{10}), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) in atmospheric pollution can cause respiratory and cardiovascular diseases, and severely cause lung cancer and death of people [8-10]. A report by World Health Organization 2021 already states that air pollution caused 1.7 million deaths in India in 2020, accounting for 16% of the annual death toll [11]. In addition, air pollution causes a certain degree of economic and social damage [12]. Xie Yang et al. found that air pollution can increase labor scarcity, resulting in an economic loss of 0.6%-2.8% related to labor supply [13]. The existing studies have shown that air pollution has typical regional and cumulative characteristics [14,15]. Whereas, regional air pollution has become the main air pollution problem in China [16], and four air pollution zones have been formed in Beijing-Tianjin-Hebei region, Chengdu-Chongqing region, Yangtze River Delta and Pearl River Delta [17]. The spatial and temporal variability of air pollutants varies significantly among regions. For example, there are differences in $PM_{2.5}$ concentrations monitored at different stations in the Beijing-Tianjin-Hebei region during periods of heavy pollution [18], and the spatial distribution pattern of $PM_{2.5}$ in the Pearl River Delta has a

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"northwest-southeast" three-level decreasing distribution [19]. At the same time, changes in the structure and layout of industrial industries will also affect the distribution pattern of air pollutants. Wang, Y. et al. analyzed that NO_2 concentration changes are significantly associated with the relocation of polluting enterprises and large events such as the Olympic Games and the World Expo [20]. Therefore, exploring the spatial and temporal variation characteristics of air pollutants can help optimize the layout of industrial industries in the region and better prevent and control air pollution in the region.

However, most of the existing studies take the Yangtze River Economic Belt, Beijing-Tianjin-Hebei, Yangtze River Delta and other key regions as the objects of exploration, and relatively few studies are yet conducted on the Chengdu-Chongqing region. As the center of gravity of China's eastern industrial transfer to take over, air pollution in the Chengdu-Chongqing region will change as a result of changes in the type and layout of industries [2]. Therefore, studying in depth the spatial distribution characteristics and causes of air pollution in Chengdu-Chongqing region is of great significance for grasping the evolution law of air pollution with industrial development, and then optimizing the industrial layout, conducting source management of air pollution and establishing the management system for air pollution prevention and control in Chengdu-Chongqing region.

Based on this, this article adopts the air quality index (AQI index) and spatio-temporal data of five major air pollutants of 16 major cities in the Chengdu-Chongqing region from 2015 to 2021 as samples, analyzes the spatio-temporal characteristics of air pollution in the Chengdu-Chongqing region using a spatial autocorrelation model, and analyzes the main sources and causes of air pollutants in different cities by the method of characteristic radar map. With the aim of providing a scientific reference basis for the coordinated promotion of high-quality economic and social development and air quality improvement in the Chengdu-Chongqing region and accelerating green development. This article is innovative in two aspects: first, in terms of research area, this paper takes urban industrial areas as the research object, focusing on the Chengdu-Chongqing region, and uses prefecture-level city data to more comprehensively explain the spatial and temporal changes and reasons of air pollution in urban industrial areas, filling the gap of existing research related to air pollution in industrial areas. Secondly, this study adopts the analysis method of characteristic radar map, which overcomes the dilemma of not being able to judge the change characteristics of pollutants directly using the conventional air quality monitoring data, and can make full use of the observed data to analyze the characteristics and causes of air pollution.

The rest of the study presents the data and methodology (Section 2), empirical results (Section 3). Finally, we draw conclusions and suggests policy implications (Section 4).

2. Data and Methods

2.1. Study Area

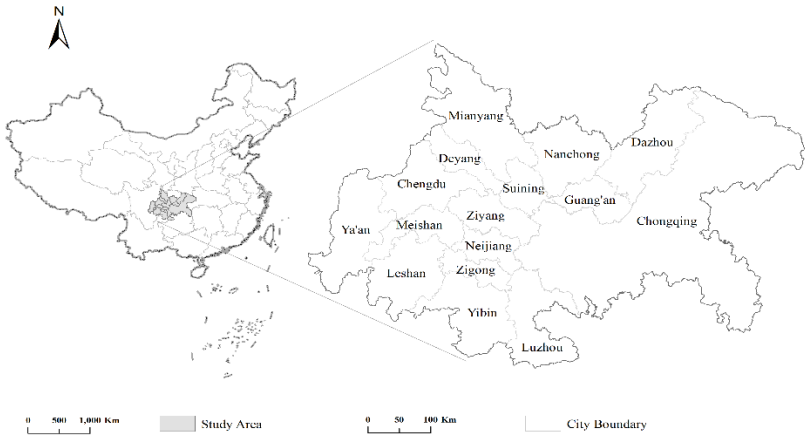

Figure 1: The geographical location map.

The Chengdu-Chongqing region is located in the upper reaches of the Yangtze River in China, in the Sichuan Basin, connected to Shaanxi-Ganxi in the north, Yunnan-Guizhou in the south, Qinghai-Tibet in the west, and Xiang-E in the east, with a total area of 185,000 square kilometers. It is an important part of China's implementation of the Yangtze River Economic Belt and the Belt and Road Strategy

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(Figure 1). Although the Chengdu-Chongqing region belongs to the subtropical monsoonal humid climate, it actually resembles the temperate maritime climate, with no scorching heat, no severe cold, and lots of rain and fog all year round. Being one of the regions with the best economic foundation and strongest economic strength in the west, according to statistics, the Chengdu-Chongqing region achieved a regional GDP of 739.92 billion yuan in 2021, accounting for 30.8% of the western region. At the same time, the Chengdu-Chongqing region is an important chemical production base, and the chemical industry has many kinds of raw materials and produces many kinds of waste, leading to a high processing difficulty factor and great difficulty in environmental management, resulting in the most direct and far-reaching impact of air pollution on people's lives in the region.

2.2. Methodology

The First Law of Geography states that geographical things or attributes are correlated with each other in spatial distribution and the closer the distance the stronger the correlation [21]. And the air pollution composition and emission levels of neighboring cities in the region will be relatively similar, making AQI values show similar short-term fluctuations, i.e., there is a spatial autocorrelation. In this article, in order to understand the spatial clustering characteristics of air pollution in the Chengdu-Chongqing region, we adopt the spatial autocorrelation analysis method with the help of Ranran He et al.'s research method [22]. Analysis of the causes of atmospheric pollution in the Chengdu-Chongqing region is carried out in this paper using the characteristic radar chart proposed by Jingchun Duan et al [23].

In particular, the spatial autocorrelation model uses Moran's I to measure the spatial autocorrelation of the AQI index in the Chengdu-Chongqing region. The local spatial autocorrelation identifies the spatial clustering characteristics of each partition and indicates the dependence of each local spatial region associated with the global general trend. Moran's I index is as follows:

$$Moran's\ I = \frac{n\sum_{n=1}^{n}\sum_{j=1}^{n}W_{ij}(x_i-\bar{x})(x_j-\bar{x})}{(\sum_{n=1}^{n}\sum_{j=1}^{n}W_{ij})\sum_{n=1}^{n}(x_i-\bar{x})^2} \quad (1)$$

Where x_j and x_j represent the observed values in regions i and j, respectively. Where n is the number of observed values and W_{ij} is the spatial weight matrix. The value of the Moran's I index is taken as (-1,1), when 0 < Moran's I < 1, it indicates the existence of positive spatial autocorrelation of cluster size layout, -1< Moran's I < 0 indicates the existence of negative spatial autocorrelation, and Moran's I=0 indicates the absence of spatial autocorrelation.

Characteristic radar chart is a method to carry out the analysis of urban pollutant sources and causes using the monitoring data of conventional air pollutants. The method is a series of mathematical algorithms to perform percentage components of conventional air pollutant monitoring data and directly present the characteristics of urban air pollution changes occurring in time series or space by designing a characteristic radar chart, so as to quickly identify the main sources and causes of urban air pollution. The specific steps are detailed in reference [23].

2.3. Data Sources

China's ambient air quality routine monitoring indicators have been expanded from three indicators to six indicators since 2013 according to GB 3095-2012 Ambient Air Quality Standards. Therefore, the air quality data (including AQI index, $PM_{2.5}$, PM_{10}, NO_2, CO and SO_2) of 16 cities (districts) in the Chengdu-Chongqing region from 2015-2021 selected for the article were obtained from the real-time monitoring data (https://www.aqistudy.cn/historydata/). The map source data in this article were obtained from the "Standard Map Service of the Ministry of Natural Resources of the People's Republic of China" (https://www.mnr.gov.cn/sj/).

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3. Results

3.1. Temporal variation characteristics of air pollutants in the Chengdu-Chongqing region

3.1.1. Interannual variation trend

The inter-annual variation of AQI index in Chengdu-Chongqing region is shown in Figure 2. The annual average value of AQI index in Chengdu-Chongqing region is between 84.33 and 66.53 from 2015 to 2021. According to the air quality classification criteria in the Technical Regulations on Ambient Air Quality Index (AQI) (Implementation), the overall interannual variation of AQI index in Chengdu-Chongqing region shows a decreasing trend, and the air quality condition is improving gradually.

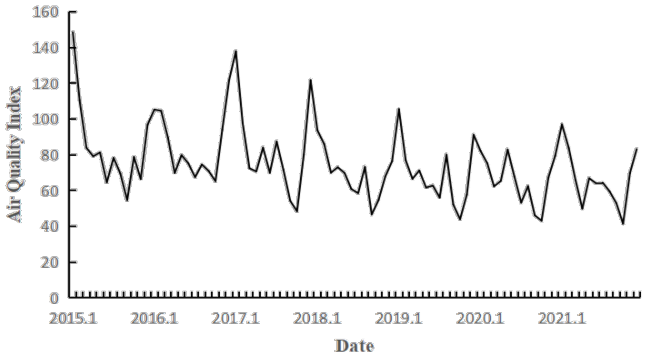

Figure 2: Long-term trends of AQI sequences in the Chengdu-Chongqing region.

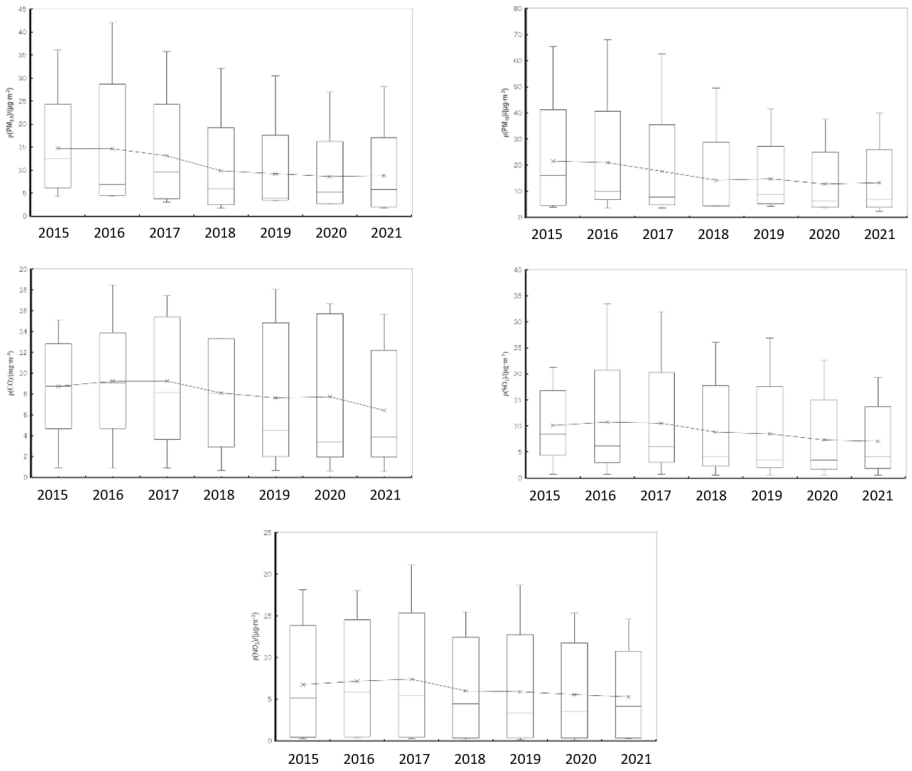

Figure 3: Interannual variations of air pollutants in the Chengdu-Chongqing region from 2015 to 2021

Further analysis of the interannual variation of $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 mass concentrations in the Chengdu-Chongqing region is shown in Figure 3. From Figure 3, it can be seen that the annual average mass concentrations of pollutants $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 in the Chengdu-Chongqing region from 2015 to 2021 show an overall decreasing trend, although they fluctuate in individual years. Compared with the annual average mass concentrations of $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 in 2015, the annual average mass concentrations of $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 will decrease by 19.53μg·m^{-3}, 31.94μg·m^{-3}, 5.02mg·m^{-3}, 3.34μg·m^{-3}, 6.39μg·m^{-3} respectively in 2021. The annual average mass concentrations of particulate matter $PM_{2.5}$ and PM_{10} will decrease by 35.35% and 36.96% respectively

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in 2021 relative to 2015. The average interannual mass concentration of $PM_{2.5}$ in the Chengdu-Chongqing region from 2015 to 2021 is 43.87, which is much higher than the national ambient air quality level 1 standard (15μg·m^{-3}), and the ratio of annual average mass concentration of $PM_{2.5}$ to PM_{10} ranges from 63.92% to 65.55%, which suggests that $PM_{2.5}$ accounts for a larger proportion of PM_{10} and is on an increasing trend. The annual average mass concentration of pollutant CO in 2015-2017 became a slowly increasing trend from 18.47mg·m^{-3} to 18.88mg·m^{-3}, and then began to decline annually, with an average annual decline rate of 8.1%. The annual average mass concentration of NO_2 shows a trend of increasing and then decreasing, rising slowly from 12.63μg·m^{-3} in 2015 to 12.71μg·m^{-3} in 2017, and then starting to decreasing to 9.29μg·m^{-3} in 2021, a value that decreases by 26.45% relative to 2015. Annual average mass concentration of SO_2 becomes a decreasing trend year by year, but in 2021 SO_2 annual average mass concentration is higher than in 2020, with an increase of 3.83%. In summary, the air pollution situation in the Chengdu-Chongqing region has gradually improved in recent years, but the problems of $PM_{2.5}$ and SO_2 pollution remain prominent. This is similar to the conclusion of Gao Lei et al. that $PM_{2.5}$ in the Chengdu-Chongqing region is a more serious pollution in the region [1]. It needs our focused attention in the future air pollution prevention and control.

3.1.2. Monthly variation pattern

The change in the monthly AQI index is shown in Figure 4. From 2015 to 2021, the monthly average AQI index of Chengdu-Chongqing region varies greatly, ranging from 53.62 to 110.01, and shows a "W"-shaped variation characteristic of "high in winter and summer, low in spring and autumn". Specifically, the AQI index rises from October to February and from May to July every year, and the air pollution situation keeps deteriorating. In particular, from October to February, the AQI index rose particularly significantly, with the index ranging from 95.74-110.01, and the air pollution was particularly serious. Spring and autumn air quality is relatively good, between 53.62-72.90 respectively.

The monthly average mass concentration of pollutants $PM_{2.5}$ and PM_{10} in the Chengdu-Yongqing area follows roughly the same trend, showing the characteristics of high in winter and spring and low in summer, with an overall "U"-shaped distribution. Except for 2016, when the highest monthly average mass concentration of pollutants $PM_{2.5}$ and PM_{10} occurred in December, the other years all occurred in January, and that the highest mass concentration in different years showed fluctuating changes, after that the monthly average mass concentration of pollutants showed a decreasing trend, with the lowest from July to September. $PM_{2.5}$ and PM_{10} pollution in winter and spring in the Chengdu-Chongqing region is more serious, mainly related to the larger emission intensity of pollution sources and relatively static atmospheric conditions[24]. Among them, the PM_{10} concentration was higher in May, which is related to the straw burning in the Chengdu-Chongqing region.

The monthly average mass concentrations of pollutants CO, NO_2 and SO_2 in Chengdu-Chongqing region follow the same trend, with fluctuating trends of falling, rising, then falling and then rising again, with high values appearing in December, January and March, and on the whole with higher concentrations in winter and lower concentrations in summer. Specifically, the monthly average concentration of the pollutant CO varied between 12.87mg·m^{-3}-21.11mg·m^{-3}, with a maximum of 21.11mg·m^{-3} in January, followed by a downward trend, falling to a minimum in July. Several studies have shown that many conditions such as lower temperatures, higher atmospheric stability, and weak solar radiation in winter are not conducive to the diffusion and reduction of pollutant CO, so that the concentration of CO is higher in winter than in the rest of the season [25,26]. The pollutant NO_2 shows the lowest monthly average concentration from June to September with a variation range of 8.67μg·m^{-3}-9.57μg·m^{-3}, after which the levels start to increase. Related studies suggest that this is due to the more frequent atmospheric circulation activity, vigorous vegetation growth, and high precipitation in summer, and the scouring effect of precipitation causes pollutant NO_2 to settle on tree canopies, the surface of water bodies, and the ground, thus resulting in lower pollutant NO_2 concentrations in summer [27]. The pollutant SO_2 in Chengdu-Chongqing region has a high monthly average mass concentration of pollutant SO_2 in December, January and March during 2015-2021, with a variation interval of 11.78μg·m^{-3}-18.61μg·m^{-3}, which becomes a decreasing trend after March and drops to the lowest value in July and August, which is related to the weakened emission intensity of pollutant sources and the exuberant atmospheric circulation in summer [28].

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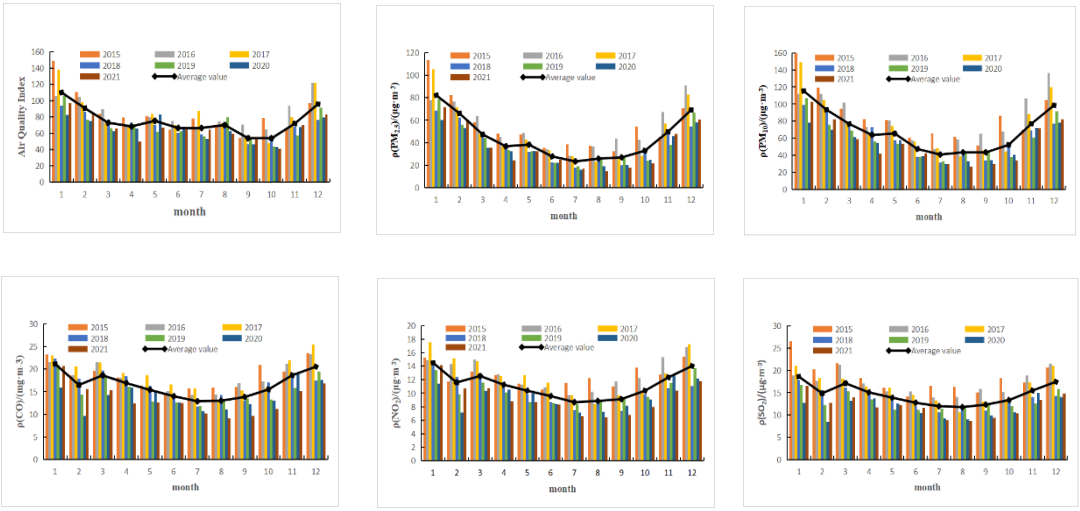

Figure 4: Monthly variations of air pollutants in the Chengdu-Chongqing region from 2015 to 2021

3.2. Spatial distribution characteristics of air pollutants in the Chengdu-Chongqing region

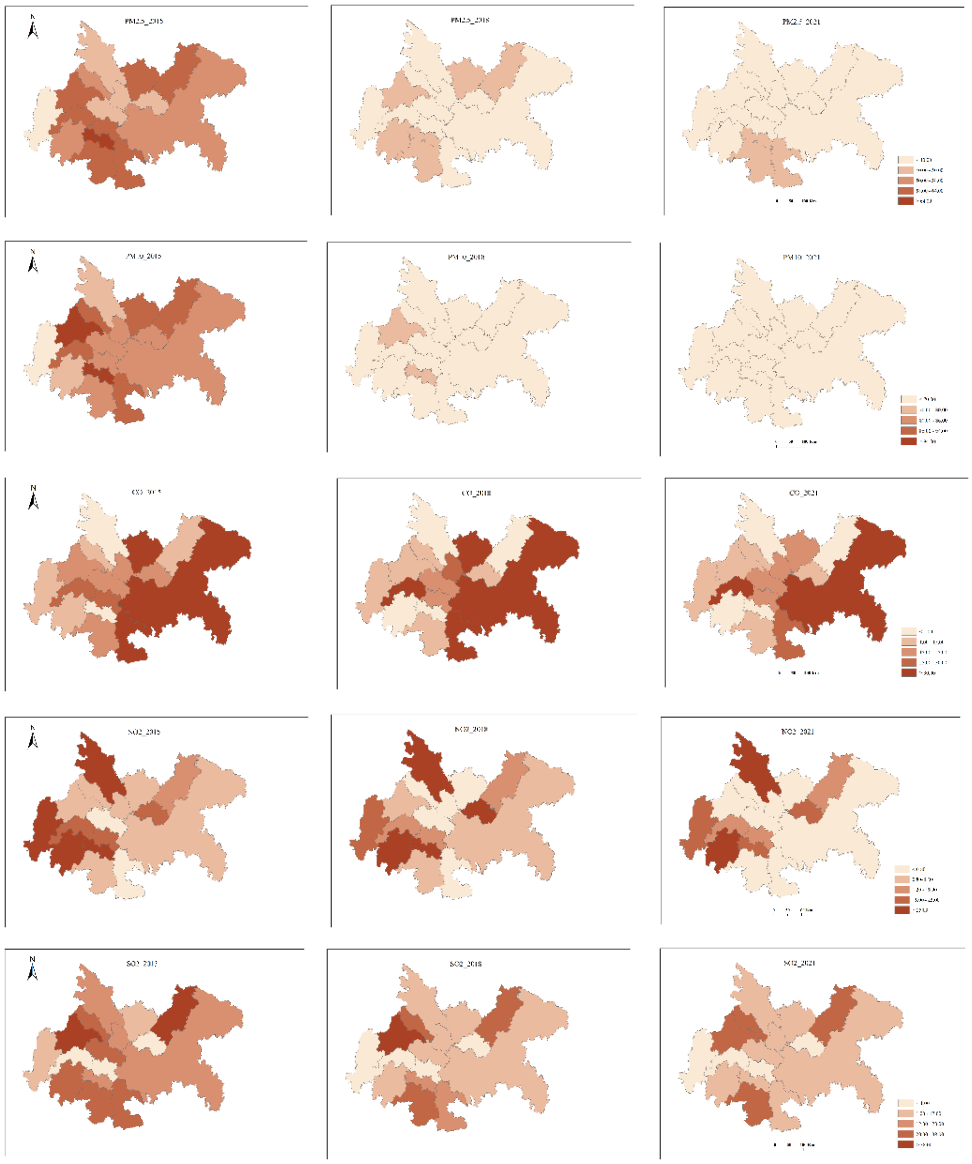

Figure 5: Spatial distributions of air pollutants in the Chengdu-Chongqing region from 2015 to 2021

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This section analyzes the spatial distribution characteristics of pollutants in the Chengdu-Chongqing region (Figure 5). The spatial distribution pattern of pollutants $PM_{2.5}$, PM_{10}, NO_2 and SO_2 present the distribution characteristics of high in the west and low in the east, which may be related to the industrial mostly chemical enterprises in western cities, as well as the blockage of the western transverse mountain range, which is not beneficial to the diffusion of pollutants. The pollutant CO shows the characteristics of high in the east and low in the west, which is mainly related to the heavy industrial structure of the eastern cities, especially Chongqing, with a large number of enterprises in iron and steel, machinery manufacturing and heavy chemical industries. The change rates of pollutants $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 present some differences spatially. The pollutants $PM_{2.5}$, PM_{10}, NO_2 and SO_2 in 16 cities in the Chengdu-Chongqing region showed an overall decreasing trend. Among them, the decline rates of $PM_{2.5}$ and PM_{10} are roughly the same in spatial distribution, and the decline trends of $PM_{2.5}$ in Nanchong and Dazhou are more obvious, while the decline trends of PM_{10} in Chengdu and Zigong are more significant. The pollutant CO in Chengdu and Chongqing shows a fluctuating upward trend, among which the upward trend in Meishan and Chongqing is significant.

Using spatial autocorrelation to analyze the clustering characteristics of the spatial distribution of AQI in 2015, 2018 and 2021 for each city in Chengdu-Chongqing region and draw scatter plots, as shown in Figure 6. Only the Moran's I index in 2021 is greater than 0.6 and significant at the 1% level, indicating that the spatial AQI index in Chengdu-Chongqing region shows the clustering characteristics of positive spatial correlation of "high-high" and "low-low". The "high-high" clusters are distributed in Yibin, Luzhou, Leshan, Meishan, Deyang, Chengdu and Zigong, while the "low-low" clusters are distributed in Ziyang, Suining, Nanchong, Chongqing, Guangyuan and Dazhou.

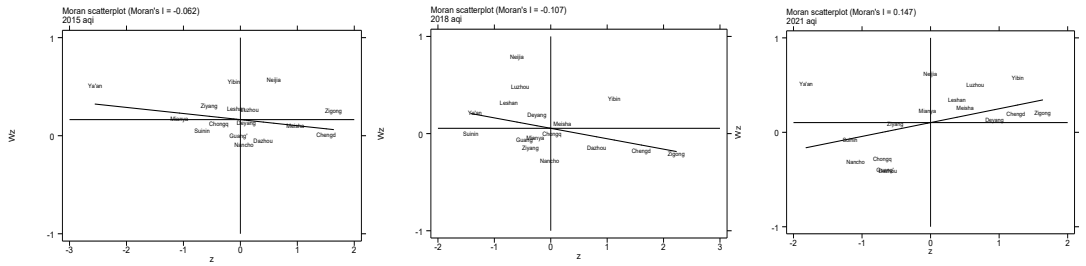

Figure 6: Scatterplot of AQI spatial distribution in Chengdu-Chongqing region in 2015, 2018 and 2021

3.3. Analysis of the causes of air pollution in the Chengdu-Chongqing region

In order to better identify the sources of urban air pollutants, this paper analyzes the causes of air pollution in the Chengdu-Chongqing region based on the regional pollution characteristic radar chart designed by Jingchun Duan et al [23], using ambient air quality monitoring data in the Chengdu-Chongqing region. The article analyzed and found that the 16 cities in Chengdu-Chongqing region can be classified into four types of air pollution: secondary (3), coal-fired(6), motor vehicle(5), and dust(2). According to the main causes of air pollution in different cities, the key measures of urban air pollution control are put forward.

Secondary type: this kind of city is mainly concentrated in Nanchong City, Dazhou City and Meishan city. The characteristics of air pollution in this category of cities are mainly characterized by exceeding the upper limit of the characteristic value of $PM_{2.5}$. $PM_{2.5}$ includes primary emissions of fine particulate matter and gaseous pollutants such as sulfur dioxide, nitrogen oxides and volatile organic compounds that generate secondary particulate matter through atmospheric chemical reactions. Since $PM_{2.5}$ sources are more complex, such as industrial production, livestock and poultry breeding, and motor vehicles are important sources of it. Therefore, these cities need to carry out continuous particulate matter monitoring and source analysis to reveal the specific local sources of $PM_{2.5}$ in depth and take targeted measures to address them.

Coal-fired type: This category mainly includes 6 cities in Chongqing, Ziyang, Leshan, Luzhou, Zigong and Mianyang, accounting for 37.5% of the total number of cities in the Chengdu-Chongqing region. The characteristics of air pollution in this region are mainly manifested as SO_2 characteristic values obviously exceeding the upper limit. SO_2 is mostly emitted from fossil fuel combustion, metal smelting, petrochemical production, etc. These cities are focused more on chemical, petroleum and machinery production industries, so the focus of air pollution control in the region is to further optimize the efforts of clean transformation and gradually promote the green development of the energy industry.

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Motor vehicle models: The cities in this category are Neijiang, Chengdu, Deyang, Guang'an and Yibin, accounting for 31.3% of the total number of cities in the Chengdu-Chongqing region. The air pollution is mainly characterized by the characteristic values of NO_2 and CO exceeding the upper limit. The combination of NO_2 and CO pollution is the main characteristic of motor vehicle emissions. These six cities are the most intensive cities in the Chengdu-Chongqing region in terms of external railroad traffic, economic trade and humanistic exchanges, and have high motor vehicle ownership. Therefore, it is necessary to further improve urban management, develop public transportation and green transportation, and accelerate the promotion of new energy vehicles to reduce vehicle emissions.

Dust type: this kind of city includes Ya'an and Suining. This type of pollution is mainly in PM_{10} Characteristic values are high or beyond the upper limit. PM_{10} mainly from the ground dust, but also including automobile exhaust, industrial and agricultural combustion dust, industrial dust and so on. Therefore, this kind of city should strengthen the control of urban dust, from the point source, point source, non-point source, mobile source and fireworks discharge control, reduce dust generation.

4. Conclusions

As the fourth pole of economic growth in China, how to promote economic growth and environmental protection together is an important issue to achieve high-quality development in the Chengdu-Chongqing region. Based on the data related to air pollutants in 16 cities in Chengdu-Chongqing region from 2015-2021, the spatial autocorrelation model and radar feature map were used to analyze the characteristics of spatial and temporal distribution and causes of air pollutants in Chengdu-Chongqing region. The analysis results show that: (1) the air pollution situation in Chengdu-Chongqing region gradually improved from 2015 to 2021, and the annual average mass concentrations of pollutants $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 showed an overall decreasing trend, but the pollution problems of $PM_{2.5}$ and SO_2 remained prominent. In terms of seasonal changes, the AQI index shows a "W"-shaped change characteristic of "high in winter and summer, low in spring and autumn", and the pollutants $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_2 show the characteristics of high in winter and low in summer. (2) There are differences in the spatial distribution of different pollutants. The spatial distribution pattern of pollutants $PM_{2.5}$, PM_{10}, NO_2 and SO_2 shows the distribution characteristics of high in the west and low in the east, while pollutant CO shows the characteristics of high in the east and low in the west, such differences are mainly related to the topography and industrial distribution. As time goes by, the pollution mitigation in each city is more obvious. (3) The air quality conditions in Chengdu-Chongqing region show clustering characteristics in 2021. The "high-high" spatial clustering exists in Yibin, Luzhou, Leshan, Meishan, Deyang, Chengdu, and Zigong; the "low-low" spatial clustering exists in Ziyang, Suining, Nanchong, Chongqing, Guangyuan, and Dazhou. The "low-low" spatial concentration exists in Ziyang, Suining, Nanchong, Chongqing, Guangyuan and Dazhou. (4) The types of air pollution in the Chengdu-Chongqing region are mainly secondary, coal-fired, motorized and dusty, among which the number of coal-fired cities is the largest, concentrated in six cities, including Chongqing, Ziyang, Leshan, Luzhou, Zigong and Mianyang, and the air pollution is mainly affected by SO_2.

Therefore, based on the findings of this paper, this paper makes the following recommendations on industrial development and air pollution prevention, control and management in the Chengdu-Chongqing region in order to help solve the air pollution problem and achieve high-quality development of economic growth and environmental protection. First, it is necessary to further strengthen the development concept of ecological and economic integration, realize ecological industrialization and industrial ecology, and balance the dual needs of economic development and environmental protection. Secondly, we should transform and upgrade heavy industries such as chemical and petroleum industries, and promote enterprises to adopt green innovative technologies and clean production of products to realize green development of energy industries. Thirdly, winter is a more serious season for air pollution in Chengdu and Chongqing, and a joint prevention and control mechanism should be established to strengthen the supervision and management of air pollution generating behaviors in winter.

Atmospheric pollution is the result of the interaction between human activities and natural factors. Changes in atmospheric pollution are not only related to regional economic conditions, residents' living habits, industrial structure characteristics and other factors, but also influenced by meteorological factors. We will further analyze the influence of these factors on the distribution of atmospheric pollution in our future research, with a view to better grasp the distribution pattern of atmospheric pollution in the Chengdu-Chongqing region and provide reference for the high-quality development of the Chengdu-Chongqing region.

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