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Long-Term Air Pollution Characteristics and Multi-scale Meteorological Factor Variability Analysis of Mega-mountain Cities in the Chengdu-Chongqing Economic Circle

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Abstract Currently, air quality has become central to global environmental policymaking. As a typical mountain megacity in the Cheng-Yu region, the air pollution in Chongqing is unique and sensitive. This study aims to comprehensively investigate the long-term annual, seasonal, and monthly variation characteristics of six major pollutants and seven meteorological parameters. The emission distribution of major pollutants is also discussed. The relationship between pollutants and the multi-scale meteorological conditions was explored. The results indicate that particulate matter (PM), SO_2 and NO_2 showed a "U-shaped" variation, while O_3 showed an "inverted U-shaped" seasonal variation. Industrial emissions accounted for 81.84%, 58% and 80.10% of the total SO_2, NOx and dust pollution emissions, respectively. The correlation between PM2.5 and PM10 was strong ($R = 0.98$). In addition, PM only showed a significant negative correlation with O_3. On the contrary, PM showed a significant positive correlation with other gaseous pollutants (SO_2, NO_2, CO). O_3 is only negatively correlated with relative humidity and atmospheric pressure. These findings provide an accurate and effective countermeasure for the coordinated management of air pollution in Cheng-Yu region and the formulation of the regional carbon peaking roadmap. Furthermore, it can improve the prediction accuracy of air pollution under multi-scale meteorological factors, promote effective emission

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WIN: wind speed; TEM: temperature; RHU: relative humidity; PRS: surface pressure; PRE: the precipitation; GST: Ground surface temperature; SSD: sunshine hours; SCB: Sichuan Basin; PRD: Pearl River Delta; YRD: Yangtze River Delta; CNAAQS: Chinese National Ambient Air Quality Standards; VOCs: Volatile Organic Compounds; WHO: World Health Organization; PM: particulate matter.

Highlights
- Variation of pollutants and multiscale meteorological parameters were investigated.
- PM2.5/PM10 and NO_2/SO_2 ratios are discussed emphatically.
- A complex "seesaw" phenomenon was found between O_3 and PM.
- The pollutant concentration far exceeds the WHO, 2021AQGs standard value.

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reduction paths and policies in the region, and provide references for related epidemiological research.

Keywords Air pollution · Carbon neutral · Chengdu-Chongqing Economic Circle · Correlation analysis · Distribution characteristics · Multi-scale meteorological variability

1 Introduction

Currently, environmental concerns are mainly focused on climate change, air quality and human health impacts, not acidification problem (Davuliene et al., 2021; Yao et al., 2020; Zhang et al., 2018). Air pollution not only has a serious impact on global and regional climate change, but also seriously threatens sustainable development and human health (Lei et al., 2022; Yuan et al., 2019; Zeng et al., 2021). Global climate change issues and human health problems caused by pollution have made air quality at the heart of global environmental policy-making (Davuliene et al., 2021; Zeng et al., 2020; Zhou et al., 2020). Related studies indicate that about 98% of cities' air quality in developing countries do not meet the standards proposed by the World Health Organization (WHO) (Ji et al., 2020; Jiang et al., 2022; Zheng et al., 2022). Besides, with the intensification of urbanization and industrialization, air pollution has become the most serious environmental and social problem in China (Fu & Chen, 2017; Guo et al., 2018; Kebin He et al., 2002; Li et al., 2021a, 2021b, 2021c). For example, outdoor air pollution lead to more than 1 million premature deaths per year (Wang et al., 2020a, 2020b, 2020c; Zheng et al., 2022). Overall, the main air pollutant in China is PM2.5, followed by PM10 and O_3 (Li et al., 2019; Wang et al., 2014; Zhao et al., 2021). Some studies indicate that if PM2.5 concentrations met WHO transition and guideline values, associated deaths would be reduced by 64% and 95%, respectively (Fang et al., 2016; Hou et al., 2022). According to the study reported by Cohen et al. (2017), PM2.5 pollution is a contributing factor to cardiovascular and respiratory diseases, including lung cancer. Cohen et al. (2005) estimated that outdoor PM2.5 air pollution is responsible for adult cardiopulmonary disease mortality (about 3%), trachea, bronchus, and lung cancer mortality (about 5%), and mortality in children under 5 years from an acute respiratory infection (about 1%) in urban areas worldwide. As the environmental pollution problem continues to intensify, the Chinese government has introduced many measures and policies to reduce air pollution (Table 1) (Kahn et al., 2022; Liu et al., 2013; Maji et al., 2018; Wang et al., 2020a, 2020b, 2020c; Yin et al., 2020a, 2020b; Zhang et al., 2014; Zheng et al., 2022).

Recently, some observational and simulation studies have pointed out that under the implementation of air pollution control measures, the concentrations of PM2.5, PM10, SO_2 and NO_2 have been effectively controlled and decreased by 22%, 21%, 53%, 5%, between 2015 and 2019 (Hou et al., 2022; Lei et al., 2022; Liu et al., 2021a, 2021b, 2021c, 2021d). However, extensive research found that between 2015–2019, in 337 major Chinese cities, O_3 concentrations increased by 20.15% (Guan et al., 2021; Hong et al., 2021). In addition, due to the significant decline in motor vehicle traffic and industrial activity levels during the COVID-19 epidemic, air pollutant emissions (such as NO_2) have been significantly reduced, but the O_3 concentration has shown a rebound trend (Chen et al., 2021; Hashim et al., 2021; Wang et al., 2021; Zhang et al., 2021). In 2020, 260 of the 337 cities had higher O_3 concentrations than in 2015, and 93 of them had an increase of more than 20% (Bekbulat et al., 2021; López-Feldman et al., 2021; Mohammed et al., 2021; Sun et al., 2022). O_3 is a secondary pollutant, it has a non-linear relationship with its precursors (VOC and NOx), and is also influenced by meteorological conditions (Liu et al., 2021a, 2021b, 2021c, 2021d, 2023; Mousavinezhad et al., 2021). In addition, air pollution in special terrain areas is a research hotspot in the world. For example, the Los Angeles Basin in the United States (Langford et al., 2010), the Sichuan Basin (SCB) (Chen et al., 2019a, 2019b; Wu et al., 2022) and the Guanzhong Basin (Yang et al., 2020a, 2020b) in China have received much attention. However, most of researches concentrated in economically developed regions in China, such as the BTH, PRD and YRD, and there are relatively few studies on air pollution of the Cheng-Yu region (Li et al., 2021a, 2021b, 2021c; Liu et al., 2020; Zhou et al., 2016).

Due to special meteorological conditions especially in summer and winter (Table S1), air pollution in SCB is still severe and is quite different from the rest of China (Ding et al., 2022; Liu et al., 2021a, 2021b, 2021c, 2021d; Wang et al., 2019a, 2019b; Yin et al., 2020a, 2020b). While the overall air quality of the Chengdu-Chongqing Economic Circle is improved, it is necessary to strengthen the joint prevention and

Table 1 Air pollution measures taken by the Chinese government

Number	Dimensions	Specific measures	Targets
1	Optimize the industrial structure	Optimize industrial layout; strictly control the production capacity of high-pollution and high-energy-consuming industries; deepen industrial pollution control; vigorously develop circular economy	Reduce air pollutant emissions
2	Adjust the energy structure	Eliminate and shut down substandard coal-fired units; improve energy utilization efficiency; promote clean coal utilization; accelerate the utilization of clean and new energy	
3	Optimize transportation system	Optimize the structure of cargo transportation; strengthen urban traffic management; promote the upgrading of oil product quality	
4	Optimize the land structure	Implement windbreak, sand fixation and greening projects; promote dust management; improve straw utilization and reduce ammonia nitrogen emission	
5	Major special action	Carry out pollution prevention of key areas in autumn and winters; carry out special actions for industrial furnaces and kilns; implement special Volatile Organic Compounds (VOCs) rectification plans	Increase air pollution control in key stages, key regions and key industries, and effectively control heavily polluted weather
6	Regional joint prevention and control	Establish and improve the regional air pollution control cooperation mechanism; strengthen the emergency linkage of heavy pollution weather, and implement peak-shift production in key industries in autumn and winter	Promoting the coordinated management of regional air pollution is conducive to controlling the transfer and diffusion of air pollutants
7	Legal system	Improve the construction of laws and regulations; improve price and tax policies; increase economic policy support	Basic guarantee for efficient control of air pollution
8	Inspector of Environmental Law Enforcement	Strengthen the quality control of monitoring data; intensify environmental law enforcement; carry out in-depth environmental protection inspections	
9	Responsibility implementation, social participation	Strengthen environmental information disclosure; actively carry out various forms of publicity and education	

control of air pollution in areas with high pollution levels, especially the megacities of Chengdu and Chongqing. Chongqing is situated at the eastern edge of the Cheng-Yu region, surrounded by mountains and undulating terrain (Li et al., 2016, 2021a, 2021b, 2021c; Lu et al., 2022a, 2022b). In addition, the land area of Chongqing is 5 times that of Beijing and 1.5 times that of the Guangdong-Hong Kong-Macao Greater Bay Area (Ding et al., 2022; Kuang et al., 2018). The frequency haze in Chongqing was 80% throughout the year (Liao et al., 2018; Liu et al., 2022a, 2022b, 2022c). So, it is known as mountainous city or foggy city. Besides, the Cheng-Yu region has introduced many air pollution control measures to improve air quality (Table S2) (Cai et al., 2018; Fu et al., 2019; Gui et al., 2019; Zeng & Zheng, 2019).


Chongqing Municipality
Beijing
Wuhan
Shanghai
Chengdu
Sichuan
Chongqing
Kunming
Guangzhou
Hong Kong
Sichuan Basin
Chengdu
Suining
Guangan
Chengyu Railway
Ziyang
Hechuan
Jingyan
Zizhong
Dazu
Chongqing
Weiyuan
Sichuan Province
Rongxian
Zigong
Fushun
Yongchuan
Chongqing Municipality

◂**Fig. 1** Locations of the Chengdu and Chongqing in the Cheng-Yu Area

The main sources of PM are industrial emissions and urban residents' activities, while NOx is mainly from industrial and traffic emissions in most megacities. As a megacity and the core area of the "Belt and Road" strategy, Chongqing ranks third in China in terms of motor vehicle ownership, and motor vehicle emissions account for 8.7% and 51.3% of total emissions in PM and NOx emissions, respectively (BEE of Chongqing, 2018). Besides, frequent biomass burning and poor topographic conditions lead to frequent high pollution days (Ding et al., 2022; Peng et al., 2020). Currently, many scholars have carried out research on the causes and driving factors of air pollution in Chongqing (Guo et al., 2021; He et al., 2017; Maji et al., 2018; Zeng et al., 2021). However, environmental pollution is the result of the comprehensive influence of multiple factors and the influencing parameters are not independent of each other (Guo et al., 2022; Kaldellis & Kapsali, 2014; Ning et al., 2019; Pinto et al., 2020a, 2020b). Even for the same research subjects, the results may be significantly biased due to the use of different research parameters and methods (Liu et al., 2021a, 2021b, 2021c, 2021d). Most of previous studies are limited to single pollutants (O_3 or PM), a few meteorological factors or short-term (1–2 years heavy pollution) studies, or focus on the form of case studies, lack of comprehensive studies on the pollution characteristics of the six criteria pollutants in the long-term series. The relationship between six criteria air pollutant and multi-scale meteorological conditions in Chongqing is unclear. In the context of the in-depth implementation of regional cooperation such as the "Chengdu-Chongqing Economic Circle" and the background of "dual carbon," choosing Chongqing, a typical mega-mountain city in the Cheng-Yu region, as the research object has theoretical prospective value. This area is also an ideal location to identify the relationship between urban meteorological elements and pollutants, and can provide a good platform for the study of air pollution under complex terrain on a global scale. More importantly, it provides accurate and effective countermeasures for the coordinated management of air pollution in China, and the realization of the "dual-carbon goal," and promotes related epidemiological research.

In this paper, six criteria pollutants (PM2.5, PM10, O_3, NO_2, SO_2, and CO) and seven meteorological parameters (wind speed (WIN), ground surface temperature (GST), temperature (TEM), relative humidity (RHU), surface pressure (PRS), precipitation (PRE), and sunshine hours (SSD)) of 21 air quality monitoring sites and 17 meteorological sites in Chongqing during 2014–2020, were comprehensively analyzed. Firstly, the long-term annual, seasonal and monthly variation characteristics of six pollutants and seven meteorological parameters were systematically analyzed by statistical analysis methods. Secondly, the annual and seasonal variation characteristics of PM2.5/PM10 and NO_2/SO_2 ratios were analyzed, and the emission distribution of the main pollutants was emphatically discussed. Finally, a comprehensive and detailed discussion of the correlation between different pollutants and multiple meteorological parameters was carried out by using various statistical methods.

2 Methodology

2.1 Study Area

The Cheng-Yu region (also known as the SCB) is located in southwest China ($25^\circ \sim 35^\circ$ N, $95^\circ \sim 110^\circ$ E), and is the intersection of the Yangtze River Economic Belt and the "Belt and Road" (Gong et al., 2021; Zhang et al., 2022a, 2022b). As one of the four major economic circles in China, the Chengdu-Chongqing Economic Circle covers an area of about 220,000 km^2, with 18 cities and more than 100 million inhabitants (Gong et al., 2021; Zhang et al., 2022a, 2022b). The unique climatic features of the region are extremely low wind speeds (0.9–1.4 m/s), low boundary layer height, high relative humidity and frequent atmospheric inversions all year round (Liao et al., 2021; Lu et al., 2022a, 2022b; Qiao et al., 2019a, 2019b). In recent years, the economy of the Chengdu-Chongqing economic circle has expanded rapidly, and energy consumption has increased sharply, forming a situation of double-high compound pollution of particulate pollution and photochemical smog. Chengdu and Chongqing are two biggest core cities in Cheng-Yu Area, located in its plat west and mountainous east, respectively (Fig. 1) and become the two most concerned cities in this region.

Chongqing ($28^\circ \sim 32^\circ$ N, $105^\circ \sim 110^\circ$ E) is a mountainous megacity located on the eastern edge of SCB. It is the main economic, manufacturing and transportation center in the upper reaches of the Yangtze

River (Chen et al., 2019a, 2019b; Harper et al., 2021; Lu et al., 2022a, 2022b). It is surrounded by mountains, and covers only 0.86% of the total land area of China, comprises more than 2.45% of the total population (Chen et al., 2019a, 2019b; Harper et al., 2021; Lu et al., 2022a, 2022b). At present, the districts and counties in Chongqing have been divided into one district and two groups according to their regional functions (Fig. 2, and 3) (Chongqing Municipal Bureau of Statistics, 2021; Zhang et al., 2022a, 2022b). In 2020, the permanent population of the main urban area is 21.15 million, and the urbanization rate reached 77.04% (Chongqing Municipal Bureau of Statistics, 2021).

From 2011 to 2020, the urbanization rate of the 21 districts in the main owed an overall growth trend, an increase of 22.52% from 2011 to 2020 (Fig. S1). Besides, Yuzhong District has the highest urbanization rate (100%), and Tongnan District has the lowest rate (58.32%) in 2020. The Yubei District has the largest population (2.20 million), and the Dadukou District the lowest (0.42 million) in 2020 (Fig. S1) (Chongqing Municipal Bureau of Statistics, 2021). Chongqing has a humid subtropical climate, with more than 100 foggy days every year, and nick-named a “Fog City.” Blocked by hills, the wind speed is extremely low (less than 2 m/s per year), and the annual average relative humidity from 2010 to 2020 is 84.02% (Fig. S2). The intensity of solar radiation has an important influence on the photochemical reaction of the atmosphere, and the sunshine duration can directly reflect the change of the intensity of solar radiation. Temperature and sunshine hours have a positive catalytic effect on the photochemical reaction to form O_3. Sufficient sunshine and strong solar radiation promote active photochemical reactions and easily cause high-concentration ozone on the ground (Tan et al., 2023; Vijay Bhaskar et al., 2018; Zhao et al., 2013). A large number of studies have shown that solar radiation and sunshine duration have decreased in recent decades, mainly due

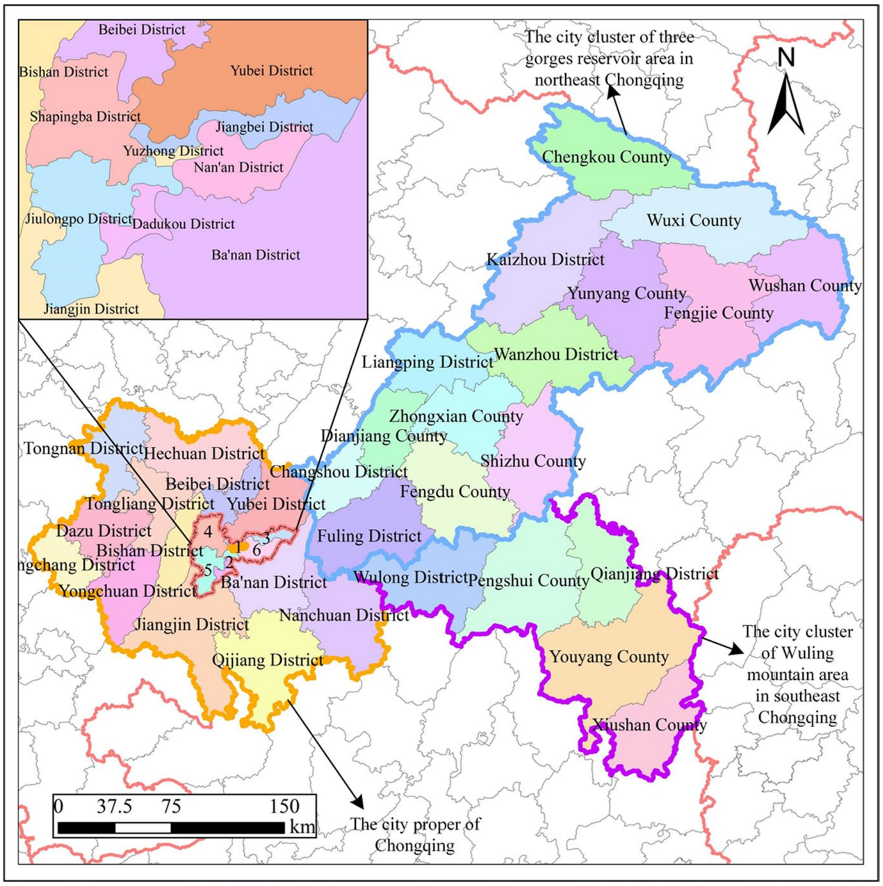


Fig. 2 Chongqing area map (one district and two groups)

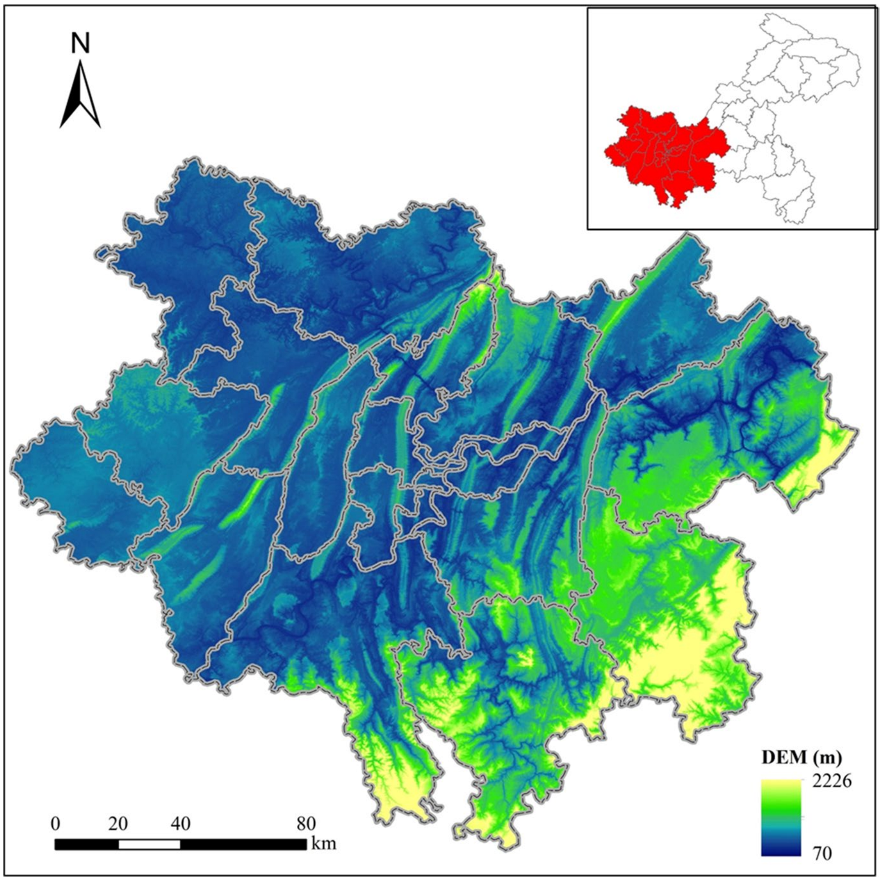


Fig. 3 Geographical location and topography of the main urban area of Chongqing

to the increase in the aerosol load of atmospheric pollutants (Lin et al., 2018; Liu et al., 2015; Zhang et al., 2015a, 2015b; Zhao et al., 2018a, 2018b). While, Chongqing experiences one of the lowest levels of sunshine in China, with only 1031.8 sunshine hours in 2020 (Chongqing Municipal Bureau of Statistics, 2021). It is also considered one of the four 'furnace cities' of China due to its long and hot summers (Harper et al., 2021).

2.2 Data Collection

Statistical analysis adopts the daily data of air quality and meteorological parameters from 2014 to 2020: concentration data of O_3, NO_2, SO_2, CO, PM2.5, and PM10 were collected from 21 air quality stations (Fig. 4); and seven surface meteorological variables (WIN, TEM, RHU, PRS, PRE, GST and SSD) were obtained from 17 meteorological stations (Fig. 5). Furthermore, In order to obtain more comprehensive and accurate data, we refer to multiple data sources (He et al., 2017; Zeng et al., 2020). Space administrative districts and basic geographic information data in the study area are based on data from the national fundamental geographic information center and geospatial data cloud (https://www.gscloud.cn). Pollutant concentration data and meteorological data were derived from different third-party sources: China National Environmental Monitoring Centre (CNEMC, http://106.37.208.233:20035), China Meteorological Data Service Center (CMDC) (CMDN, http://data.cma.cn), and China Weather Network (www.weather.com.cn). In addition, the Environmental Quality Report issued by Chongqing Environmental Protection Bureau (http://www.cepb.gov.cn/) and Sichuan Environmental Monitoring Center (http://www.cnemc.cn/) was also referenced. The socio-economic data mainly obtained from the National Bureau of Statistics of China, Sichuan and Chongqing Statistical Yearbooks.

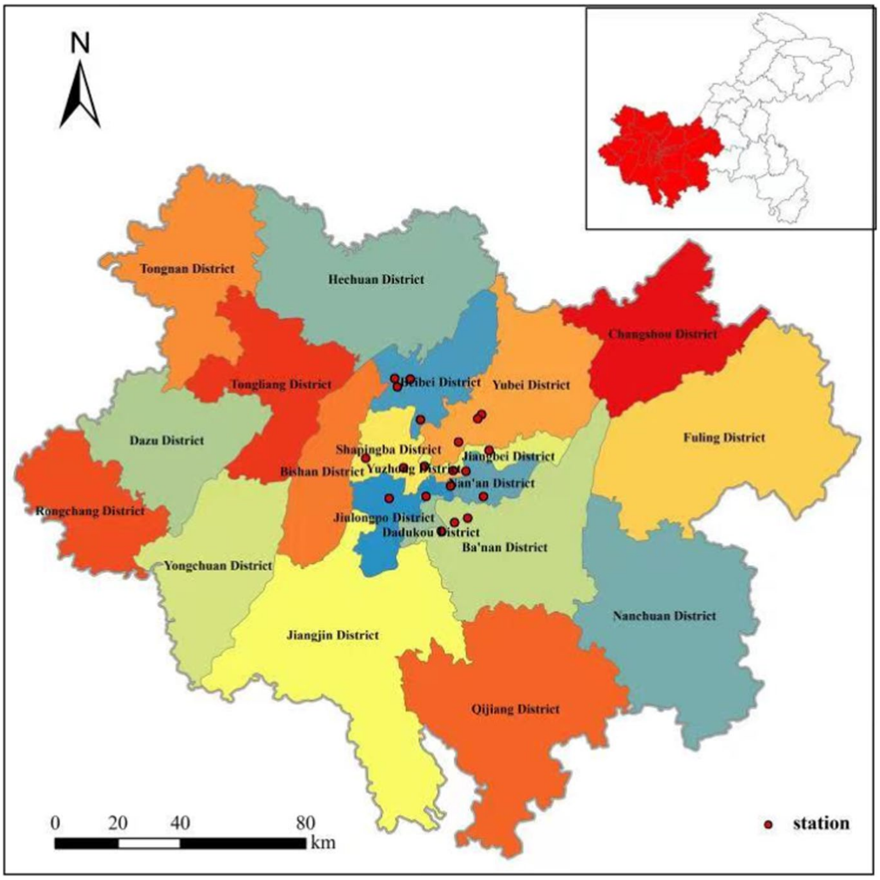


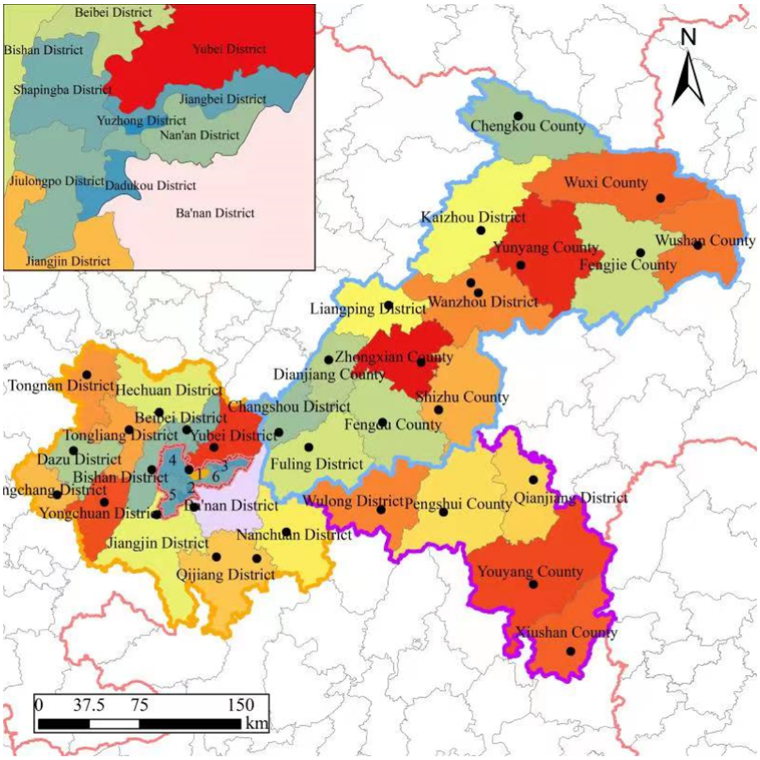
Fig. 4 Air quality monitoring sites in 21 districts of the main urban area

2.3 Analysis Methods

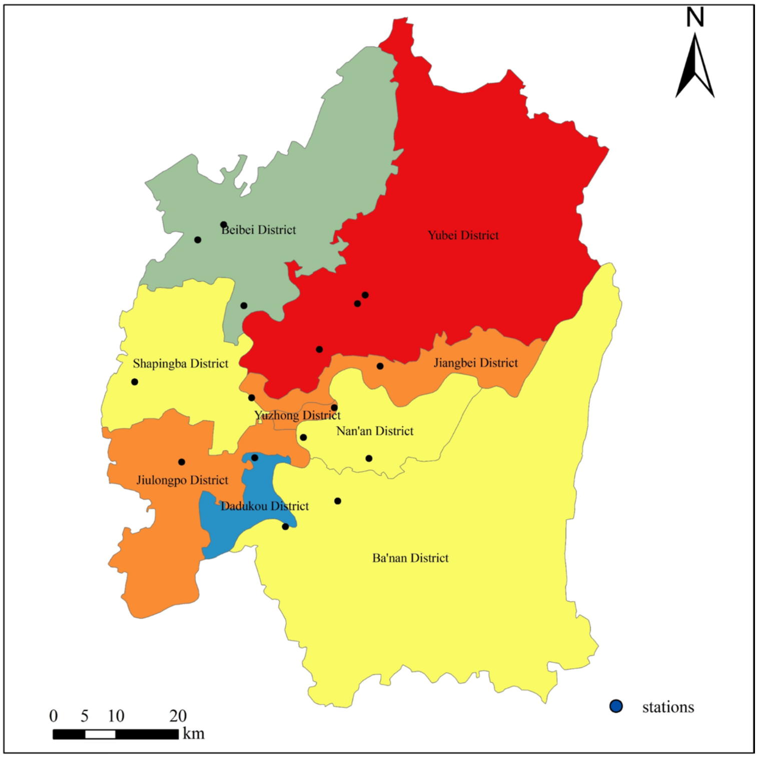
In this study, the 12 months were divided into four season categories (spring, summer, autumn and winter) (Kuang et al., 2018; Lu et al., 2022a, 2022b). The validity of environmental monitoring data strictly follows Chinese national standards GB 3095–2012 and GB/HJ 663–2013, HJ /T 193—2013 (Maji et al., 2018; Zhao et al., 2021). Meteorological monitoring data follows relevant ground meteorological observation specifications. The percentage of time series missing data for the observed concentrations is low. Because the inverse distance weighting method depends on the power value of the inverse distance, the calculation method is relatively simple, it is difficult to reflect special values, and it is easily affected by extreme values. While, Kriging interpolation considers the positional relationship between the observed point and the estimated point in the interpolation process, and also considers the relative positional relationship between the observation points, and the interpolated grid is smoother. Previous studies have shown that kriging interpolation results are better than distance-weighted inverse ratio interpolation results (Lee, 2022; Lin et al., 2022; Kumar et al., 2018; Tarasov et al., 2018). Therefore, the missing data were processed with monitoring data from neighboring stations through the Kriging interpolation method.

Furthermore, statistical analysis and abnormal value determination of sample data were carried out with the national standard GB/T 4883 of the People's Republic of China (Statistical interpretation of data-Detection and treatment of outliers in the normal sample, GB/T 4883-2008, 2009). Additionally, the data were checked by comparison with historical data (Chen et al., 2018; Davuliene et al., 2021). On the other hand, this study uses the latest international standards (WHO, 2021AQG) as the evaluation standard for the excess of major pollutants. The annual, seasonal and monthly variation characteristics of atmospheric pollutants and meteorological

Fig. 5 Chongqing meteorological monitoring station



(a) Meteorological stations in Chongqing



(b) Meteorological station in the central urban area of the main city

parameters were statistically analyzed by Excel, Origin, SPSS and ArcGIS. According to the monthly average value, the correlation between pollutants and their correlation with meteorological factors were discussed by Pearson correlation analysis and linear regression analysis.

3 Results and Discussion

3.1 Air Pollution Characteristics

Compared with 2014 (119 days), the non-attainment days in 2020 (33 days) showed a substantial decrease over 72.27% (Fig. 6). This is contributed by the fact that the adoption of a number of environmental protection measures in Chongqing in recent years (Table S2). In addition, it can be seen from Fig. 6 that the concentrations of PM2.5, PM10, SO_2, and CO all showed an obvious downward trend during the study period. From 2014 to 2020, PM2.5 and PM10 pollution concentrations dropped significantly, by 49.23% and 45.92%, respectively. Among gaseous pollutants, SO_2 saw a clear-cut decrease, falling by 66.67% from 24 to 8 μg/m^3 between 2014 and 2020, CO also presented a decrease trend (dropped 38.89%). Compared with 2014 (146 μg/m^3), the annual average concentration of O_3 in 2020 (150 μg/m^3) has increased by 2.74%. The annual average concentration of NO_2 in 2014 and 2020 is both 39 μg/m^3. However, due to the control measures taken by the government, O_3 and NO_2 showed a downward trend during the COVID-19 epidemic in 2020 compared to 2019, down 2.5% and 4.46% respectively. Overall, the change trend of NO_2 is relatively stable, and vehicle emission is the major contributor to NOx and VOC (Kuerban et al., 2020; Si et al., 2019; Li, 2018). Relevant literature shows that 45% of the NOx emissions in the urban area of Chongqing come from motor vehicle emissions (Liu et al., 2022a, 2022b, 2022c; Wang et al., 2012). For O_3, the change range is more obvious. Studies have shown that the rise in O_3 may be contributed by the emission of precursor substances such as NO_2 and VOCs (Deng et al., 2019; Küçükaçıl Artun et al., 2017; Yu et al., 2020). In addition, the reduction of PM2.5 slowed down the deposition of hydrogen peroxide radicals and promoted the formation of O_3 (Qiao et al., 2021; Shen et al., 2020; Yu et al., 2019). The complex "seesaw" phenomenon between O_3 and PM can be inferred that the improvement of air quality in the next few years will require coordinated control of PM2.5 and O_3.

On the other hand, there was a significant seasonal heterogeneity in O_3 and PM concentrations during the study period. PM2.5 and PM10 showed similar seasonal trends, with more dramatic changes in autumn

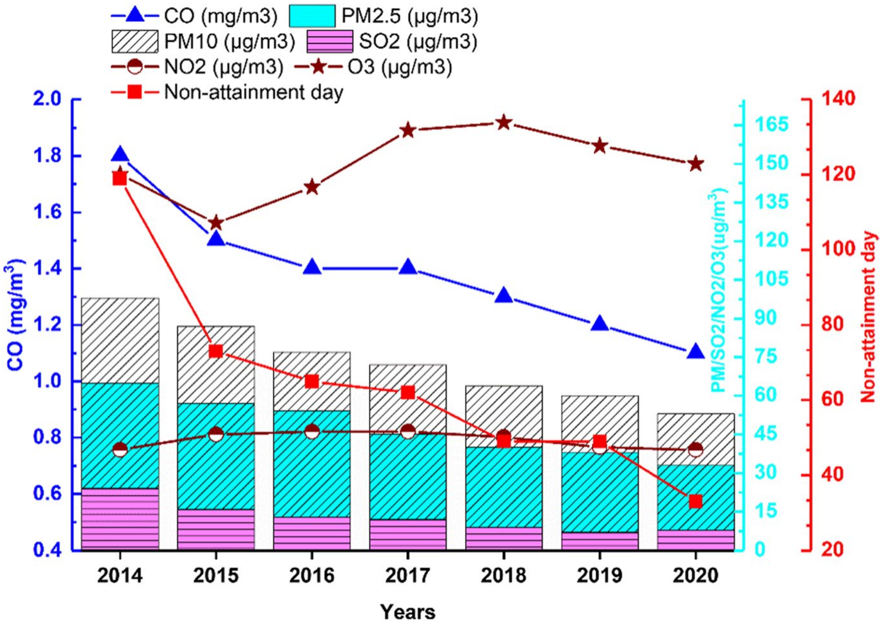


Fig. 6 Variation of critical pollutants concentration in Chongqing

and winter (Fig. 7). The PM2.5 concentration value in all seasons beyond the CAAQS Grade I standard (15 μg/m^3), and was much higher than the WHO, 2021AQGs (5 μg/m^3). In addition, the PM2.5 value in winter is higher than CAAQS Grade-II standard (35 μg/m^3), which is about 12 times that of WHO, 2021AQGs (5 μg/m^3). The concentration of PM10 in four seasons also exceeded WHO,2021AQGs (15 μg/m^3), and the winter value was higher than CAAQS Grade I standard (40 μg/m^3). The concentration of NO_2 is much higher than the value of WHO, 2021 AQGs (10 μg/m^3), and also exceeds the value of CAAQS (40 μg/m^3). The results show that PM and NO_2 pollution are far from the standard limit values of WHO,2021AQGs, and at the same time seriously exceed the CAAQS Grade. Some existing studies have shown that biomass combustion and residential coal have a significant impact on Chongqing's air quality, especially in winter (Ding et al., 2022; Hu et al., 2019a, 2019b; Peng et al., 2020; Yamada et al., 2008). Besides, the frequent occurrence of stagnant meteorological conditions in winter makes it easy for pollutants to accumulate, resulting in serious pollution (Kuerban et al., 2020; Lu et al., 2022a, 2022b).

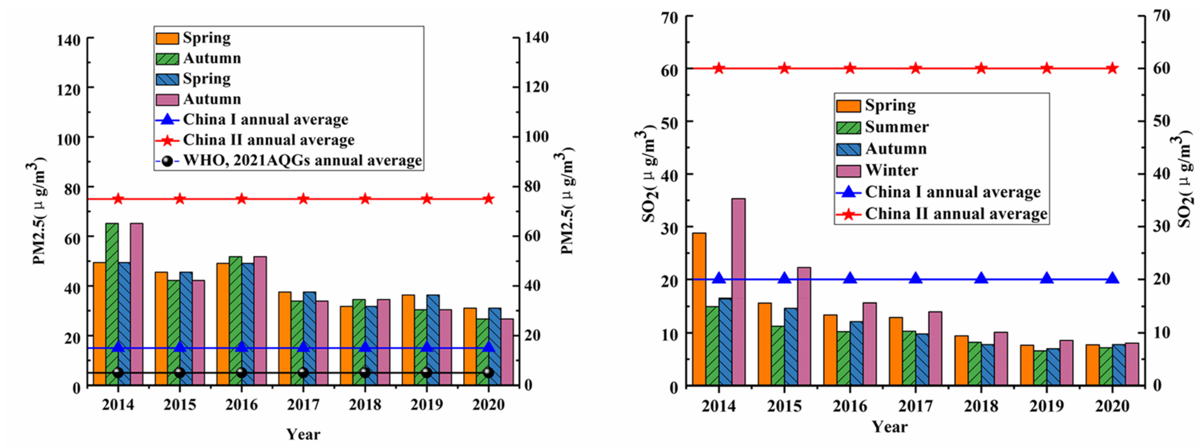
In contrast, the seasonal pattern in O_3 was clearly contrast to other pollutants, with a generally higher level observed in summer, which was same as the findings of Qiao et al., (2019a, 2019b). Besides, the value is higher than WHO, 2021AQGs and CAAQS Grade I limit (100 μg/m^3) in all seasons except winter. A few studies have also pointed out that the rise in O_3 concentrations in summer was probably caused by strong solar radiation and the increases in VOCs or NOx emissions (Jiang et al., 2018; Liu et al., 2022a, 2022b, 2022c; Tan et al., 2018). Furthermore, the latest research points out that the abundance of O_3 in Chongqing has slightly raised in recent years, possibly due to the decrease in PM (Feng et al., 2019; Lu et al., 2022a, 2022b; Zhou et al., 2019). The seasonal difference of SO_2 concentration was non-obvious, but exhibited a slight downward trend during the study period. This is mainly due to flue gas desulfurization technology, application of electrostatic precipitators and elimination of low-efficiency generator units (Kuerban et al., 2020). There was no significant change in CO concentration. In general, PM, SO_2 and NO_2 showed a "U-shaped" seasonal variation trend, while O_3 showed an "inverted U-shaped." The amount of NOx control reduction is far behind the amount of motor vehicle emissions, so continuous emission reduction of NO_2 should be strengthened. In addition, the prevention and control of O_3 pollutants should be strengthened in summer, and the control of PM pollutants should be emphasized in autumn and winter.

3.2 Correlations Between Air Pollutants

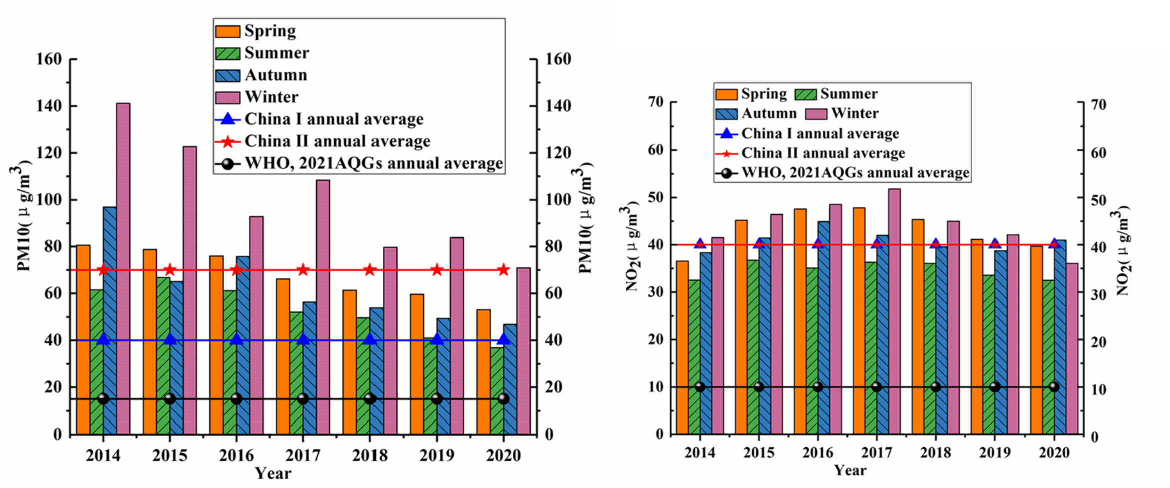
3.2.1 PM2.5/PM10 Ratio

Different from the analysis of pollution characteristics of a single pollutant, ratio analysis can analyze related pollution characteristics and identify the source of pollutants (Li et al., 2007; Xia et al., 2016). The ratio analysis commonly used to explore the characteristics of air pollutants mainly includes PM2.5/PM10 and NO_2/SO_2 (Chen et al., 2015; Yang et al., 2019a, 2019b, 2019c). To a certain extent, the PM2.5/PM10 ratio can indirectly provide some guidance for exploring particulate matter composition, source contribution and removal process (Fan et al., 2021; Zhan et al., 2019). In addition, the PM2.5/PM10 ratio is often used as an important indicator for analyzing the contribution of PM2.5 to PM10 in atmospheric particulates (Lu et al., 2022a, 2022b).

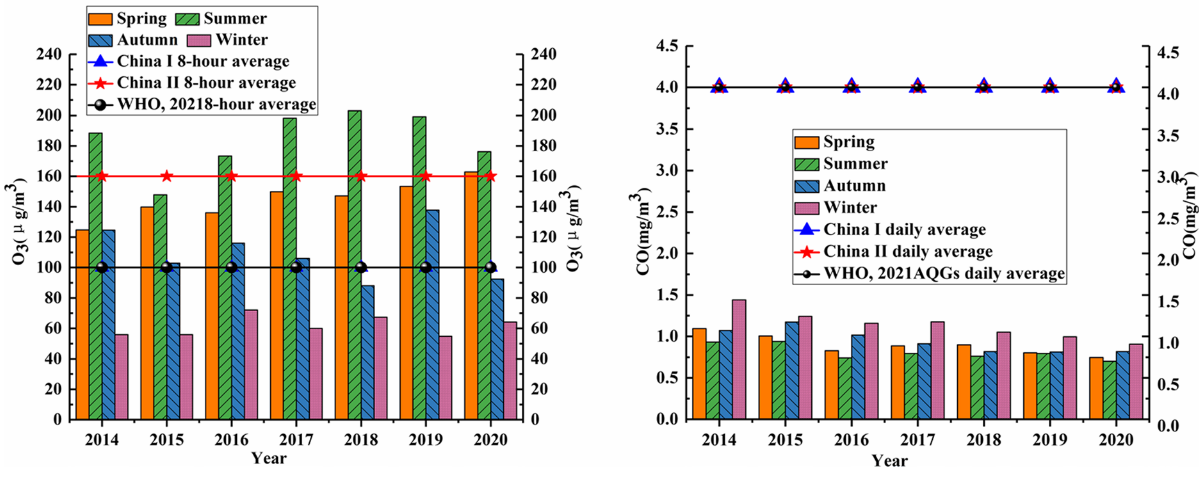
Although the number of non-compliance days and PM concentrations displayed a significant downward trend between 2014 and 2020, the PM2.5/PM10 ratio was still in the range of 0.6–0.7, with a maximum ratio of about 0.70 in 2016 (Fig. 8). Relevant studies have shown that the larger the ratio of PM2.5/PM10, the more seriously the area is polluted by PM and the worse the air quality (Fan et al., 2021; Li et al., 2016; Zhan et al., 2019). Referring to the relevant standards (Ramanathan et al., 2001), PM2.5/PM10 values between 0.3 and 0.4 indicate light pollution; ratios between 0.5 and 0.7 indicate serious pollution. The average ratio of PM2.5/ PM10 between 2014 and 2020 was 0.65, indicating that the area is heavily polluted by PM2.5 and PM10, and the air quality is poor. High PM2.5/PM10 ratios may also originate from different combustion processes, such as coal and biomass fuels (Fan et al., 2021; Li et al., 2016; Zhan et al., 2019). This conclusions are consistent with and extend those of previous studies: Lu et al., (2022a, 2022b) reported PM2.5/PM10 ratios higher than 65% during 2013 and 2017 for most of the 17 stations investigated in Chongqing (Lu et al., 2022a,



(a) PM2.5 (d) SO_2



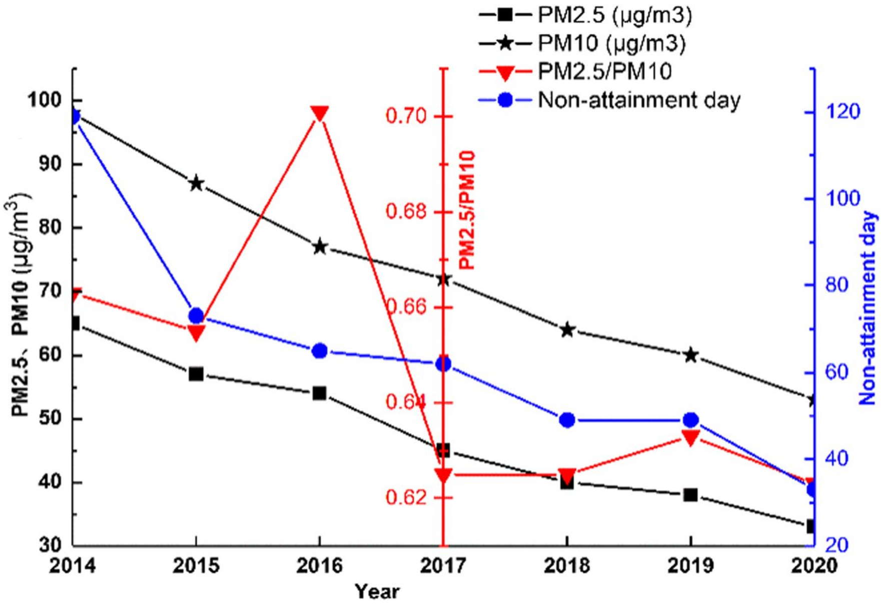
(b) PM10 (e) NO_2



(c) O_3 (f) CO

Fig. 7 Seasonal mean mass concentrations of six pollutants from 2014 to 2020

Fig. 8 Variation in the annual PM2.5/PM10 ratios



2022b). In general, the proportion of PM2.5 in particulate matter is still large, and further strengthening of governance is required.

There were obvious seasonal differences in PM2.5/PM10 ratio, which was higher in winter (0.6–0.8) and lower in summer (0.5–0.63) (Fig. 12). The maximum value of PM2.5/PM10 ratio in the four seasons all appeared in 2016, indicating that the PM pollution was more serious in that year. In 2016, the annual average concentration of PM2.5 reached 63.42 μg/m^3, and the pollution was the most serious in winter. The incidents of PM2.5 pollution in this year were more prominent. For example, from December 26, 2015 to January 6, 2016, and from December 4 to 14, 2016, the daily average concentration of PM2.5 exceeded the national secondary standard. Furthermore, 2016 is the beginning year of China's "Thirteenth Five-Year Plan." Pollution improvement measures are still in the implementation stage and the results are not obvious. So, PM2.5 is still the main pollutant in this year. In addition, it can be observed that the ratio of PM2.5/PM10 is winter > autumn > spring > summer (Fig. S3). Except for 2015 and 2018, the PM2.5/PM10 ratios showed a "U-shaped" change trend in other years. This ratios in winter were all greater than 0.6, and a high ratio indicated that there was more PM2.5 in the atmosphere in winter. This is related to increased particulate matter emissions due to increased fuel consumption in winter (Hua et al., 2018; Wang et al., 2006). In addition, this region has low precipitation and high humidity (about 80%) in winter, which favors the transformation of primary pollutants into particles (Chen et al., 2013; He et al., 2011).

3.2.2 NO_2/SO_2 Ratio

The NO_2/SO_2 ratio can explain the energy structure characteristics of a region. NO_2 mainly comes from mobile sources such as vehicle exhaust emissions (Gu et al., 2019; Sun et al., 2020), while SO_2 mainly comes from stationary sources such as power generation, burning coal and industrial production (Hu et al., 2017; Shuma & Madyira, 2019; Yang et al., 2019a, 2019b, 2019c). Sources of pollutants can be identified by analyzing changes in NO_2/SO_2 ratio. A higher NO_2/SO_2 ratio indicates that the pollutants are mainly from mobile sources, and a lower ratio indicates higher stationary sources. In addition, the ratio can also reflect the effect of regional coal suppression and sulfur control and the changing characteristics of automobile emission pollution. A high ratio of NO_2/SO_2 indicates the presence of a large number of vehicles and more NOx emissions (Gu et al., 2019; Sun et al., 2020; Zhao et al., 2019).

Between 2014 and 2019 the NO_2/SO_2 ratio in showed an upward trend (Fig. S4). During the study period, the NO_2/SO_2 ratio were all greater than 1, and reached 5.7 in 2019. This also shows that the city's SO_2 has been significantly reduced, and NO_2 emissions have shown an increasing trend. The car ownership in Chongqing in 2020 increased by 42.3% compared with 2014 (Chongqing Municipal Bureau of Statistics, 2021), which may be the main reason for the increase in NO_2 (Baudic et al., 2016; Liang et al., 2019; Lu et al., 2022a, 2022b). Previous studies have revealed that in Chongqing, motor vehicle emissions account for more than 30% of the PM2.5 and NOx (Ding et al., 2021; Liu et al., 2022a, 2022b, 2022c). The gradual rise in the NO_2/SO_2 ratio also demonstrate that mobile emissions (vehicle emissions) contribute more to pollution than stationary sources (power generation and industrial production). Since desulfurization equipment is widely used in industry and power plants, SO_2 in the SCB has shown a clear downtrend after 2007 (Zhao et al., 2019). Besides, there are obvious seasonal differences in NO_2/SO_2 ratio. The ratios were higher in summer and autumn in 2014–2015, and higher in spring and autumn than in summer and winter in 2016–2020 (Fig. 9). These seasonal differences are mainly related to emissions from industrial, motor vehicle and urban domestic sources. In addition, it is also affected by the complex terrain and meteorological factors of the SCB. Overall, the NO_2/SO_2 ratios showed an obvious increasing trend in all four seasons, indicating that the NO_2 emission was still serious. Although the emission reduction of SO_2 and NOx in Chongqing is relatively large, the grow in the number of vehicles and total power consumption has resulted in poor control of NOx. Furthermore, high concentrations of SO_2 and NO_2 will accelerate PM2.5 pollution (Kuerban et al., 2020; Li et al., 2022; Wang et al., 2016), so Chongqing should continue to strengthen the continuous emission reduction of NO_2.

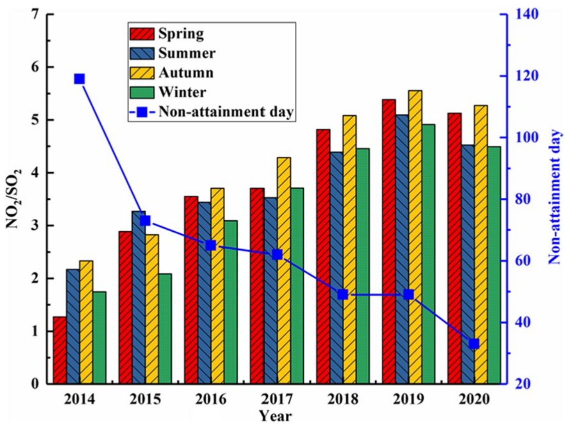


Fig. 9 Seasonal variation of NO_2/SO_2 ratio

3.2.3 *Emission Sources of Pollutants*

Besides meteorological conditions, emissions from residential, industry, transportation and power affect air quality as well. Yang et al., (2019a, 2019b, 2019c) pointed out that while reducing industrial and transportation emissions can slash SO_2 and NO_2, respectively, reducing residential emissions is also critical for mitigating PM and CO pollution in western China (Yang et al., 2019a, 2019b, 2019c). From 2010 to 2020, Chongqing's population (3.3% growth) and GDP (about 2 times growth) both showed an upward trend (Fig. S5). The total energy usage increased by 52.82% compared to 2010 and 2020. Coal and electricity consumption showed an upward trend, with an increase of 20% in electricity and 32.6% in coal. In addition, pollutant concentrations in most cities are related to traffic emissions. Compared to 2010 the car ownership in 2020 increased by 1.77 times in Chongqing.

From 2010 to 2020, the main sources of pollutant emissions in Chongqing include industry, urban life and motor vehicle emissions. The total amount of SO_2 emission is about 43.63 million tons and the main contributing sources are industrial sources and urban living sources, of which the industrial source emissions accounting for 81.84% of the total emissions. Chongqing is one of the most developed industrial regions in China's inland areas, and coal is the main energy source. Compared with 2010, SO_2 emissions in 2020 dropped sharply by about 90.62%, indicating a significant reduction effect (Fig. S6). The emissions from industrial sources showed a significant drop feature year by year, but the emissions from urban life sources show certain fluctuations. In recent years, Chongqing's industry has continuously improved desulfurization equipment, and the effect of SO_2 emission reduction is obvious. However, the use of coal in daily life should be controlled to further realize the continuous emission reduction of SO_2.

Besides, the total NOx emissions in Chongqing showed a downward trend year by year. Compared with 2011, the 2020 decreased by about

58.52% (Fig. S7). The main emission sources of NOx are industrial sources > motor vehicle pollution sources > urban living sources. Among them, industrial emissions and motor vehicle emissions accounting for 58% and 38.06% of the total emissions, respectively. In addition, industrial emissions show a significant downward trend, with a drop of about 75.77% in 2020 compared to 2011. The downward trend of motor vehicle emissions is relatively stable, showing a certain upward trend between 2011–2014 and 2015–2019. After 2016, the emission of motor vehicles was higher than that of industrial sources and became the main contributor to NOx. Mobile sources such as motor vehicles have become the main sources of PM2.5 and NO_X pollution in Chinese cities. Although numerous measures have been taken to reduce NOx emissions, NOx concentrations are still high due to the steady increase in traffic intensity and the shift from gasoline to diesel vehicles. Therefore, the emission reduction of automobile pollution will be the focus of Chongqing's "14th Five-Year Plan", and it is also a difficult point. Finally, industrial pollution sources are the main contributors to dust. From 2010 to 2020, the amount of industrial dust accounted for 80.10% of the total emissions, and the urban living sources and motor vehicle pollution sources accounted for a small proportion (Fig. S8). Total dust emissions in 2011–2015 and 2018–2019 showed an upward trend, mainly due to the increase in industrial emissions.

3.2.4 Correlations Between Air Pollutants

(1) PM2.5 and PM10

Pearson correlation coefficient (R) (Table S3) (Kuerban et al., 2020; Yangyang et al., 2015) were used to test the correlations between PM and the gaseous pollutants, and to explore the annual and seasonal correlations of various air pollutants from 2014 to 2020. The Pearson correlation coefficients (R) were established between PM2.5, PM10, and the gas pollutants in Chongqing (Table 2). PM10 was positively correlated with PM2.5 ($R = 0.980$), indicating a very strong correlation between them (Table 2). Similar findings have also been reported in previous findings (Li et al., 2015; Yang et al., 2019a, 2019b, 2019c).This is because PM2.5 is a component of PM10, and they have similar sources and pollution transformation rules, which also indicates that there is a certain synergy in the emission of particulate matter with different particle sizes. In order to further discuss the internal relationship between PM10 and PM2.5, with PM2.5 as the dependent variable, the monthly average mass concentration values of PM2.5 and PM10 were used for linear regression analysis. There is a relatively obvious linear correlation between them ($R^2 = 0.961$), the regression equation is: $y = 10.16 + 0.8x$ (Fig. 10). Besides, $R = 0.98$, which further indicates that the linear correlation between PM is very strong, and the regression effect

Table 2 Correlations of pollutants based on annual and seasonal data in 2014–2020

Pollutants	PM10	SO_2	NO_2	CO	O_3
Yearly					
PM2.5	0.980	0.709	0.515	0.822	-0.520
PM10		0.758	0.534	0.825	-0.444
SO_2			0.228	0.774	-0.229
NO_2				0.464	-0.462
CO					-0.586
Spring					
PM2.5	0.946	0.760	-0.011	0.624	-0.883
PM10		0.808	0.073	0.801	-0.934
SO_2			-0.409	0.884	-0.881
NO_2				-0.231	0.090
CO					-0.832
Summer					
PM2.5	0.980	0.689	0.483	0.623	-0.576
PM10		0.801	0.457	0.710	-0.521
SO_2			-0.007	0.756	-0.253
NO_2				0.135	-0.181
CO					-0.367
Autumn					
PM2.5	0.996	0.879	0.027	0.716	0.371
PM10		0.891	-0.003	0.714	0.366
SO_2			0.079	0.939	0.204
NO_2				0.252	-0.218
CO					0.142
Winter					
PM2.5	0.993	0.961	0.243	0.969	-0.466
PM10		0.941	0.289	0.965	-0.496
SO_2			0.066	0.956	-0.352
NO_2				0.347	0.181
CO					-0.293

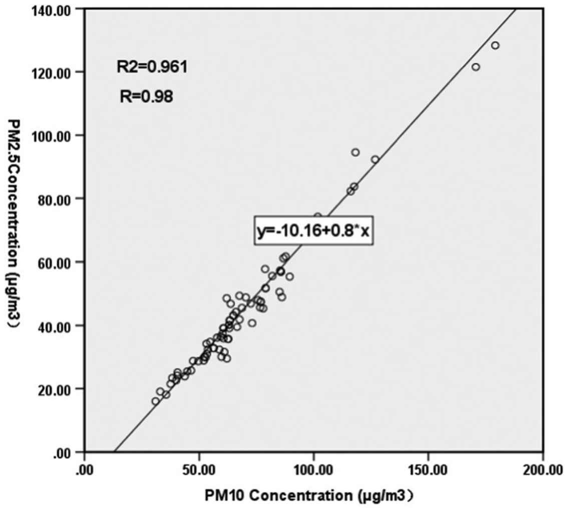


Fig. 10 PM2.5 and PM10 linear regression analysis

is good. It can be postulated that PM2.5 and PM10 exist in a complex relationship.

(2) PM and gaseous pollutants

PM was only significantly negatively correlated with O_3 and positively correlated with other gaseous pollutants (SO_2, NO_2 and CO). The Pearson correlation coefficients between PM with NO_2, SO_2 and CO were either high or moderate ($R > 0.5$), indicating that they have a high degree of homology (e.g., fossil fuel combustion; (Mulay et al., 2019)). It has been pointed out that NO_2, SO_2 and CO emissions are often accompanied by PM emissions (Ibe et al., 2020; Karimi & Shokrinezhad, 2020; Shen et al., 2020). These gaseous pollutants are also important precursors of atmospheric particulate matter, which can generate secondary particulate matter through chemical or photochemical reactions in the air, and their contribution to atmospheric particulate matter cannot be ignored (Lei et al., 2022; Tian et al., 2019). The emission reduction of gaseous air pollutants such as NOx, SOx, and NH3 has a certain promotion effect on the generation of particulate matter (Davuliene et al., 2021). O_3 was negatively correlated with the other five pollutants, but it shows a significant anti-correlation with PM (PM2.5: $R = -0.520$; PM10: $R = -0.444$). Besides, SO_2 is positively correlated with NO_2 and CO, which is related to the fact that these three pollutants all come from fossil fuel combustion and vehicle exhaust emissions. NO_2 and CO showed a significant positive correlation, indicating that they have similar sources. There are different correlations between pollutant concentrations in different seasons. Both PM2.5 and PM10 showed strong seasonal correlation (Spring: $R = 0.946$; Summer: $R = 0.980$; Autumn: $R = 0.996$; Winter: $R = 0.993$). PM is more sensitive to the variation of NO_2 in summer and winter.

(3) The relationship between O_3 and NO_2

O_3 is mainly a secondary pollutant produced by complex atmospheric photochemical reactions of precursors such as NOx and VOCs produced by man-made daily emissions, motor vehicle emissions, and industrial production (Santos et al., 2021; Wang et al., 2022; Yang et al., 2021). NO_2 is an important precursor pollutant for the formation of O_3, and complex photochemical cycle reactions can occur among NO, NO_2, and O_3. The correlation between O_3 and NO_2 is a moderate correlation ($R = -0.462$). The fact that O_3 and NO_2 have an opposite trend indicates that NO_2 is the precursor pollutant for the formation of O_3, and a large increase in the content of O_3 in the atmosphere will consume a large amount of NO_2, resulting in a decrease in the content of NO_2. On the other hand, it shows that the mass concentration of O_3 in the atmosphere is also affected by other factors (such as VOCs and solar radiation). In summer, strong solar radiation, high temperature, and intense NO_2 photolysis reaction lead to an increase in the concentration of precursors for O_3 in the atmosphere and generate a large amount of O_3. On the contrary, in winter, the temperature is low, the sunshine time is short, the solar radiation is weak and the static wind frequency is high, and the atmospheric photochemical reaction conditions are poor, so that the precursors such as NOx can only be slowly converted into O_3. The concentration of O_3 in the atmosphere is high, that is, the concentration of precursors that generate O_3 will also increase, and a large amount of NO_2 will be consumed correspondingly, thereby reducing the concentration of NO_2 in the atmosphere. Therefore, there is a negative correlation, and it also shows that within a certain range, reducing NO_2 emissions will lead to an increase in ozone concentration.

The change of NO_2 concentration in the atmosphere is not only consumed by the generation of O_3

precursors, but also closely related to meteorological conditions, industrial production activities and other factors. NO_2 in the city mainly comes from motor vehicle emissions. As the number of motor vehicles continues to rise, nitrogen oxide pollution in Chongqing is on the rise. Therefore, controlling traffic emissions is the key to improving air pollution in this region. In addition, a large number of studies have shown that the evolution of O_3, NOx, and VOCs has characteristics such as nonlinearity, non-stationary, and complexity (Han et al., 2020; Hao et al., 2018; Jiang et al., 2018; Liu et al., 2022a, 2022b, 2022c; Mao et al., 2022; Tan et al., 2018; Zhou et al., 2022). Therefore, to reduce the concentration of O_3 pollution, the precursors VOCs and NOx cannot be controlled simply. Mastering and understanding the sensitivity relationship between O_3 and precursors (NOx and VOCs) is an important aspect of O_3 prevention and control.

3.3 Effects of Meteorological Factors on the Air Pollutants

3.3.1 Variation Characteristics of Meteorological Parameters

Meteorological conditions are an important factor affecting more than 70% of pollutant concentrations in China (Li et al., 2016). The multiscale interactions of meteorological conditions affect the formation, migration, and distribution of atmospheric pollutants in complex ways (He et al., 2017; Mishra & Goyal, 2016; Wang et al., 2020a, 2020b, 2020c; Yang et al., 2019a, 2019b, 2019c). Exploring the relationship between meteorological factors and air pollutants is of great significance for proposing more "precise" air pollution control measures. Due to differences in pollutant concentrations and meteorological conditions on different time scales, it is important to investigate their temporal variations before analyzing the relationship between them.

Wind speed Wind not only plays a role in transporting pollutants, but also is the most direct factor determining the diffusion of pollutants in the atmosphere (Kong et al., 2020; Zeng & Zhang, 2017; Zhan et al., 2019). The higher the wind speed, the stronger the ability of air pollutants to diffuse and dilute. In addition, wind speed is also one of the dominant factors affecting the dry deposition of atmospheric particulate matter (Yang et al., 2020a, 2020b). Li et al. (2016) pointed out that the incidence of haze was significantly negatively correlated with wind speed (Li et al., 2016). The monthly average wind speed in Chongqing is mostly in the range of 1–2 m/s, the maximum wind speed in summer is 1.7 m/s, and the minimum wind speed in winter is about 0.9 m/s. The annual average wind speeds from 2014 to 2020 were 1.4 m/s, 1.74 m/s, 1.68 m/s, 1.67 m/s, 1.76 m/s, 1.71 m/s, and 1.70 m/s, respectively. In addition, during the study period, the lowest annual average value of 17 stations appeared at Beipei station, and the highest value found at Qijiang. There are annual differences in the annual wind speed of each station, but it is not significant, and most of the wind speeds are between 1.0 m/s and 2.5 m/s.

Relative humidity and temperature Changes in relative humidity can affect atmospheric stability, which in turn affects atmospheric convection and vertical diffusion, causing fluctuations in particle concentrations. Previous studies have shown that the hygroscopicity of aerosols is positively correlated with relative humidity (Lin et al., 2019; Tan et al., 2013; Wang et al., 2020b). The higher the relative humidity, the stronger the extinction and scattering abilities of the aerosol, and the lower the atmospheric visibility. The relative humidity in Chongqing was relatively high (about 80%), and there was no significant difference among the 17 sites (Fig. S9). An increase in relative humidity will exacerbate air pollution, as Li et al. (2016) research have declared that humidity is positively correlated with aerosol concentrations (Li et al., 2016). From Fig. S10, it can be concluded that the change trend of relative humidity from 2014 to 2020 is stable (about 80%), and the minimum relative humidity change is not obvious (about 60%). There are certain seasonal differences in the average relative humidity and the minimum relative humidity between 2014 and 2020 (Fig. 11). The seasonal trend of average relative humidity from 2016 to 2018 was consistent, and the rest of the years showed an inverted “U”-shaped seasonal change. Besides, the average relative humidity was the largest in autumn and winter (about 85%), which may be caused by the lower temperature and greater precipitation in autumn and winter. For the minimum relative humidity, the seasonal variation trend is almost the same as the

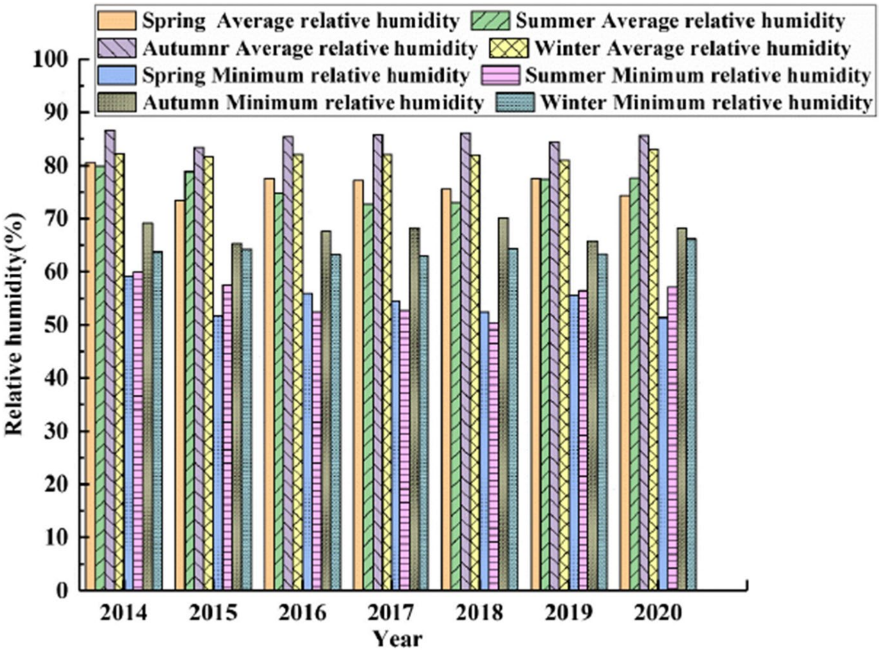


Fig. 11 Seasonal variation of RHU

average relative humidity, and the value is larger in autumn and winter.

The atmospheric environment has regional characteristics, and temperature is closely related to pollution concentration by affecting atmospheric turbulence and chemical reactions (Ma & Jia, 2016; Mukherjee et al., 2020). The increase in temperature can intensify the exchange of atmospheric turbulence, thereby promoting the horizontal transport and vertical diffusion capacity of the atmosphere (Lin et al., 2019; Pouliot et al., 2015; Wang et al., 2020a). Under high temperature conditions, air convection and particle Brownian motion are more intense, and the particle concentration is lower. The average temperature of the 17 stations is about 18℃, and the Jiangjin station has the largest value in each year (Fig. S11). The temperature also has obvious seasonal variation characteristics. The temperature also showed an inverted "U"-shaped monthly variation trend, with the highest temperature in summer (July and August) and the lowest in winter (January and December) (Fig. S12).

Precipitation and sunshine duration Relevant studies have shown that rainfall can clean the air pollutants and is a wet removal (or wet deposition) process, so it is a meteorological element that maintains the relative stability of atmospheric components (AzadiAghdam et al., 2019; Prasad et al., 2016; Zhang et al., 2017). During the study period, the precipitation at each station had a certain variation difference (Fig. 13). As shown in Fig. S13, the precipitation showed an inverted "U"-shaped seasonal variation. Summer is considered to be the rainy season, and its precipitation affected by the monsoon is significantly higher than other seasons (Harper et al., 2021). The winter precipitation is the lowest and significantly lower than other seasons. The highest monthly precipitation occurred in July 2020, followed by June 2016 (Fig. S14). The sunshine duration from 2014 to 2020 showed the features of "double peaks" and "double valleys." The values were higher in 2016 and 2018 and lower in 2014, 2017 and 2020 (Fig. S15). In addition, the seasonal trend of each year is basically the same, showing an inverted "U" shape (Fig. 12).

Ground surface temperature and pressure There was no significant difference between the average surface temperature (about 20 °C) and the minimum surface temperature (about 15 °C) from 2014 to 2020 (Fig. S16). But, the average surface temperature, daily maximum and minimum temperature values were distinctly bigger in summer than in other seasons,

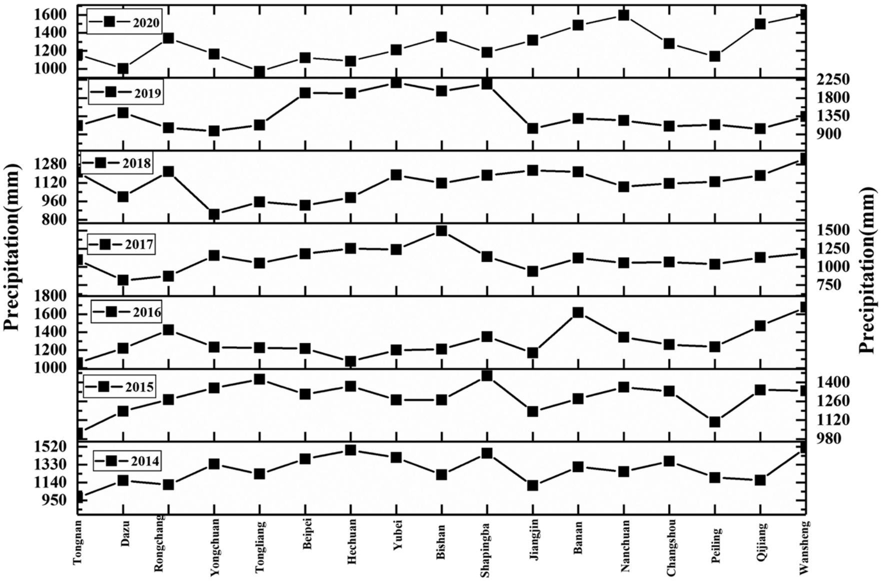


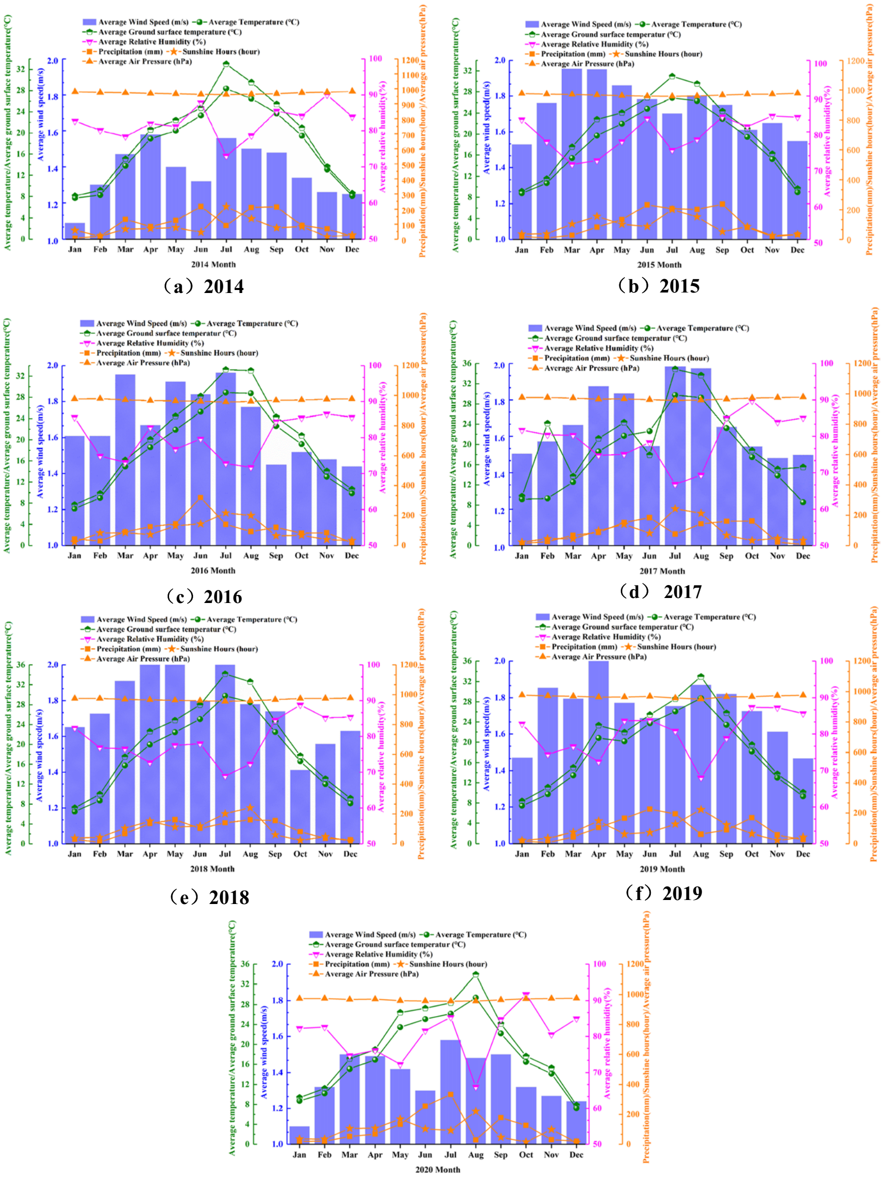
Fig. 12 2014–2020 Annual PRE in 17 stations

and lowest in winter, with little difference between spring and autumn (Fig. S17). Atmospheric pressure is an important factor affecting the concentration of pollutants. When the air pressure is high, there are many sinking airflows on the ground, which is easy to form a sinking temperature inversion layer, and it is difficult for pollutants to move and dilute to the upper atmosphere (Graham et al., 2023; Guo et al., 2022; Jury, 2020). It can be seen from Fig. S18 that during the study period (2014–2020), the average, daily maximum and minimum values of atmospheric pressure at the same station had no obvious annual changes, but there were certain differences among stations during the same period. The annual variation of the average pressure of each station is basically consistent, indicating that atmospheric pressure is not the main factor affecting the difference of pollution concentration among the stations. The average pressure fluctuated slightly between 2014 and 2020, and compared with 2014 (971 hPa), the decrease in 2020 (966 hPa) was reduced by about 0.05%. The difference in atmospheric pressure at each station is related to factors such as the location of the station and its temperature (Cheng et al., 2022; Jury, 2020; Salvador et al., 2021). This also shows that meteorological factors are interrelated.

3.3.2 *Relationship Between Meteorological Conditions*

Meteorological conditions are an important factor affecting the level of regional air pollution. Chongqing is a large mountainous city located in the SCB, changeable weather conditions such as cold air interception, low-level jet stream, valley wind and interstitial wind are important factors affecting the air quality of this region (Lu et al., 2022a, 2022b; Wang et al., 2017; Zhou et al., 2019). Meteorological elements fluctuated during the study period, among which SSD, PRE and RHU changed greatly, and PRS changed relatively smoothly. The changes of TEM and RHU were basically the same, indicating that there was a certain relationship between them. From Fig. 13, it can be seen that each meteorological element has different monthly variation characteristics in the same year except PRS. Among them, the monthly changes of TEM and average GST showed an inverted "U"-shaped change, and the values in July and August were higher than those in other months. The average relative humidity is lower in the northeast of the main urban area of Chongqing (Baishiyi, Shapingba, Jiangjin District), which may be affected by the warm temperate climate of Shanxi Province connected to

Fig. 13 Monthly variation of meteorological parameters from 2014 to 2020



（a） 2014

（b） 2015

（c） 2016

（d） 2017

（e） 2018

（f） 2019

（g） 2020

the north. In addition, the southern region (Jiangjin District, Wansheng District) connected to Guizhou Province has higher average temperature and precipitation in each year than other regions, which may be related to the meteorological conditions of warm and humid precipitation in Guizhou Province connected to the south. Furthermore, the average pressure values in the southeast (Nanchuan District) and south (Wansheng District) are lower than those in other regions. Overall, PRE, SSD, TEM and GST are the biggest in summer and the lowest in winter. There is a positive correlation between SSD and TEM ($R = 0.796$), and the correlation is extremely strong (Table 3).

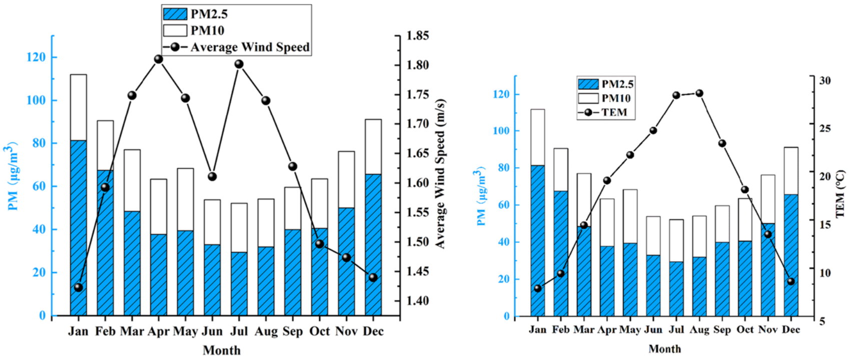
3.3.3 Relationship between air pollutants and meteorological conditions

Relationship between PM pollutants and meteorological factors It can be seen from Table 3 that PM were significantly negatively correlated with wind speed (PM2.5: $R = -0.392$; PM10: $R = -0.346$) and

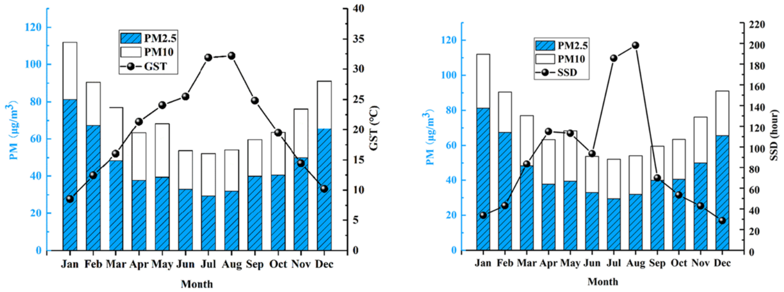
Table 3 Correlation matrix between PM and meteorological parameters based on monthly data in 2014–2020

Pollutants	WIN	TEM	RHU	PRE	SSD	GST	PRS
Yearly							
PM2.5	-0.392	-0.677	0.241	-0.546	-0.472	-0.649	0.692
PM10	-0.346	-0.617	0.181	-0.513	-0.395	-0.594	0.640
WIN		0.444	-0.591	0.242	0.537	0.467	-0.517
TEM			-0.437	0.722	0.796	0.970	-0.923
RHU				0.043	-0.814	-0.484	0.546
PRE					0.338	0.659	-0.671
SSD						0.826	-0.804
GST							-0.901
Spring							
PM2.5	-0.095	0.195	0.477	0.187	-0.617	0.406	0.622
PM10	0.051	0.369	0.377	0.181	-0.516	0.526	0.634
WIN		0.309	-0.172	0.219	0.101	-0.461	-0.388
TEM			-0.666	-0.568	0.477	0.085	-0.179
RHU				0.645	-0.952	0.354	0.762
PRE					-0.454	0.187	0.229
SSD						-0.295	-0.798
GST							0.782
Summer							
PM2.5	0.343	-0.114	0.147	0.269	0.219	0.035	0.423
PM10	0.276	-0.161	0.171	0.209	0.168	0.00	0.569
WIN		0.593	-0.762	-0.529	0.860	0.687	0.059
TEM			-0.885	-0.478	0.896	0.979	0.131
RHU				0.706	-0.914	-0.918	-0.172
PRE					-0.530	-0.519	-0.240
SSD						0.957	0.244
GST							0.265
Autumn							
PM2.5	-0.244	0.425	0.271	0.329	0.107	0.035	0.646
PM10	-0.288	0.435	0.296	0.406	0.103	0.032	0.656
WIN		0.327	-0.654	-0.318	0.193	0.498	-0.230
TEM			-0.605	0.553	0.666	0.801	0.176
RHU				0.032	-0.429	-0.641	0.370
PRE					0.226	0.276	0.329
SSD						0.920	0.337
GST							0.200
Winter							
PM2.5	-0.255	0.149	-0.136	-0.346	0.320	-0.187	0.853
PM10	-0.197	0.178	-0.167	-0.382	0.282	-0.157	0.801
WIN		0.347	-0.718	0.394	0.408	0.394	-0.362
TEM			-0.294	-0.019	0.058	0.912	-0.230
RHU				0.103	-0.301	-0.263	-0.014
PRE					0.666	-0.009	-0.05
SSD						-0.065	0.537
GST							-0.511

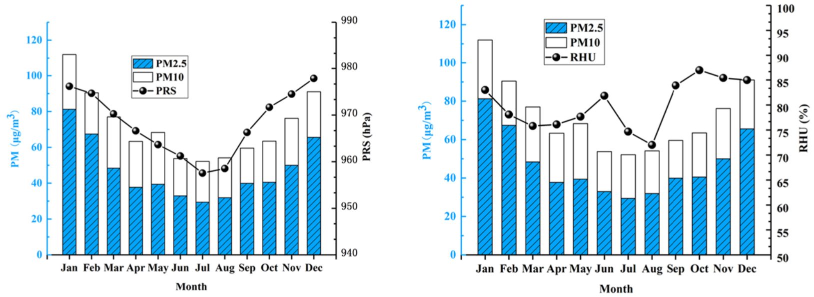
PRE (PM2.5: $R = -0.546$; PM10: $R = -0.513$). Wind contributes to the dilution and three-dimensional transport of atmospheric pollutants (Atwood, 2012; Martins et al., 2016; Yang et al., 2018). Usually, the air quality is better due to the dilution effect of the wind. In addition, because the strong wind easily stirs the dust, the smaller the probability of haze weather, the better the air quality condition (Fig. 14). This may be related to the fact that with the increase of wind speed, the stability of the atmosphere is destroyed, the horizontal diffusion rate of water vapor and pollutants is accelerated, and the visibility is correspondingly



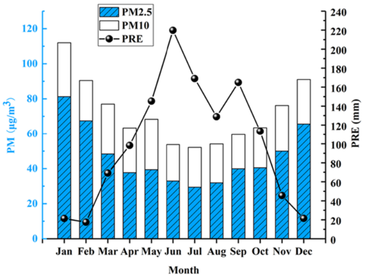
(a) WIN **(b) TEM**



(c) GST **(d) SSD**



(e) PRS **(f) RHU**



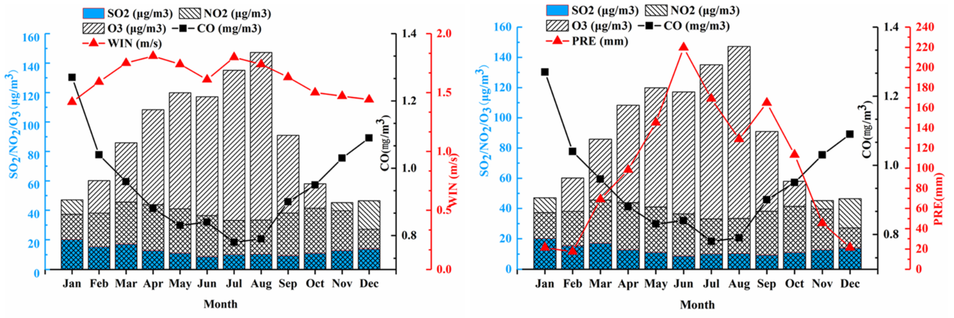
(g) PRE

Fig. 14 Monthly relationship between PM pollutants and meteorological parameters improved (Shuangchen et al., 2017; Zhao et al., 2018a, 2018b). Conversely, calm winds and breezes will inhibit the diffusion of atmospheric pollutants and increase the mass concentration of atmospheric particulate matter. Besides, it also indicating that the greater the rainfall, the more obvious the cleaning effect on atmospheric particulate matter, and the more conducive to reducing the concentration of atmospheric particulate matter (Fig. 15). This results are same as the findings of Yang et al., (2019a, 2019b, 2019c), that increased precipitation improves the wet removal of pollutants and therefore also reduces pollutant concentrations (Yang et al., 2019a, 2019b, 2019c).

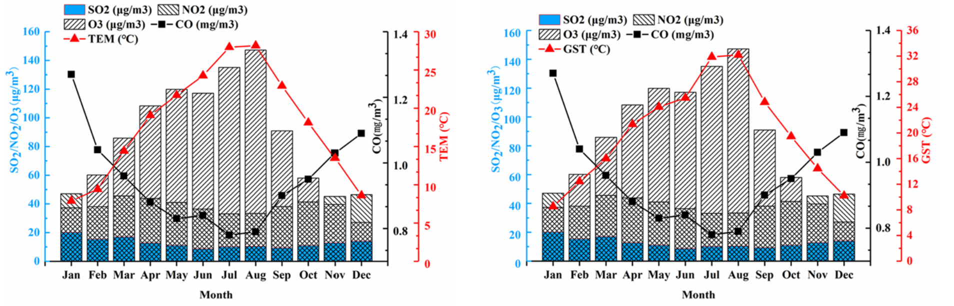
PM2.5 and PM10 were remarkably negatively correlated with TEM, GST and SSD (TEM:PM2.5: $R=-0.677$, PM10: $R=-0.617$; GST:PM2.5: $R=-0.649$, PM10: $R=-0.59$; SSD: PM2.5: $R=-0.472$, PM10: $R=-0.395$) indicating that the higher the TEM, GST and sunshine time, the lower the PM concentration (Table 3). Moreover, studies have also demonstrated that the rising temperature will cause the concentration of pollutants to increase, because the high temperature environment can cause the chemical reaction of the precursors of atmospheric particulate matter (such as SO_2, NO_2) to generate secondary particulate matter, resulting in secondary pollution (Jeong & Park, 2013; Mishra & Goyal, 2016; Wang et al., 2015). Except in summer, PM was positively correlated with TEM. The reason may be related to the high temperature in Chongqing in summer (Fig. 15), the rising movement of the atmosphere due to heating, which is easy to develop into atmospheric convective movement and generate wind (Zhan et al., 2019; Zhang et al., 2015a, 2015b).

Furthermore, PM concentration is only positively correlated with PRS (PM2.5: $R=0.692$, PM10: $R=0.640$) and RHU (PM2.5: $R=0.241$, PM10: $R=0.181$) (Table 3). This shows that the higher the PRS and RHU, the worse the air quality. When the PRS is high, the upward movement of PM is inhibited by the downward airflow, resulting in the formation of high concentrations of particulate matter. RHU reflects the water vapor content in the air, and high-humidity air is more likely to cause heavier air pollution, which is consistent with the conclusion that the concentration of particulate matter is positively correlated with RHU (Hu et al., 2019a, 2019b; Zhai et al., 2019; Zhao et al., 2018a). High relative humidity and high water vapor content are beneficial to the secondary transformation of precursors and the retention of atmospheric particles in the air (Hu et al., 2019a, 2019b; Yang et al., 2018). The fine particles become larger in size by hygroscopic effect, and the concentration in the air increases accordingly. Besides, PM and PRS have a very strong correlation in winter (PM2.5: $R=0.853$, PM10: $R=0.801$), and a small correlation in summer (PM2.5: $R=0.423$, PM10: $R=0.569$). In winter, the temperature is low, and a downdraft is formed in the center. The near ground is controlled by high air pressure (Fig. 14), the atmospheric structure is relatively stable, and the temperature inversion is strong, which inhibits the diffusion of atmospheric pollutants (Hu et al., 2019a, 2019b; Jiang et al., 2019; Ning et al., 2019). Therefore, high-pressure meteorological conditions can promote the accumulation of atmospheric particulate matter, which in turn leads to poor air quality in winter. In summer, the low-pressure control center is formed near the ground, which is facilitate the diffusion of pollutants and reduces the concentration of particulate matter (Ning et al., 2018; Zhao et al., 2010).

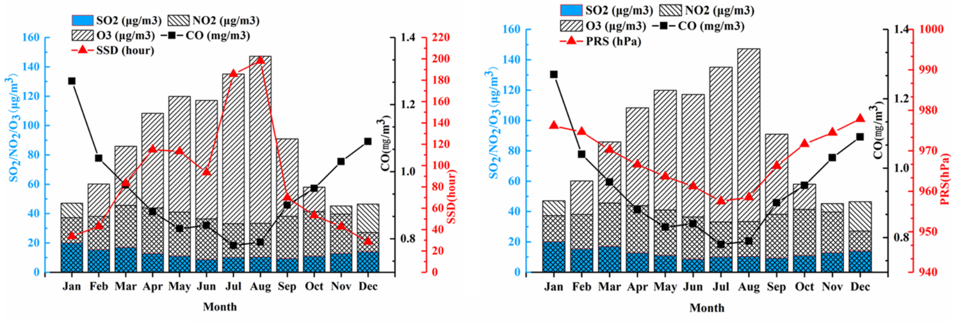
Relationship between gaseous pollutants and meteorological factors SO_2, NO_2, and CO all showed different negative correlations with wind speed, PRE, GST, and SSD, but presented positive correlations with TEM (Table 4). Compared with other pollutants, O_3 showed a significant positive correlation with wind speed ($R=0.522$) and PRE ($R=0.540$) (Table 4). This is due to the efficient removal of PM by high WIN and increased solar radiation, thereby, aggravating the formation of O_3 (Yang et al., 2020a, 2020b; Zhang et al., 2015a, 2015b). In addition, due to the seasonal differences in precipitation, the effects on pollutants show different correlations in different seasons. Numerous studies have shown that rising temperatures promote the diffusion of air pollution (Ngabura et al., 2018; Zeng & Zhang, 2017; Zhan et al., 2019; Zhao et al., 2019). It can be found that NO_2 is significantly negatively correlated with TEM ($R=-0.578$), which may be caused by a large amount of O_3 depleting NO_2 during high temperature and long sunshine (Zhao et al., 2019). Contrary to other gaseous pollutants, O_3 has a significant positive correlation with TEM ($R=0.873$),



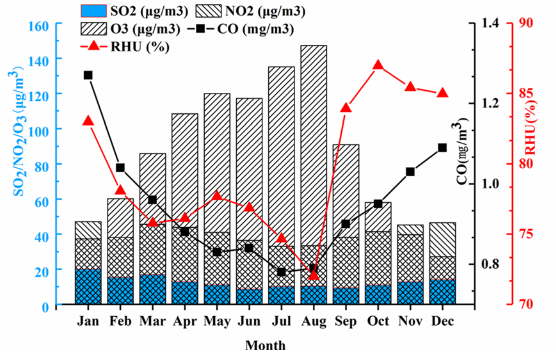
(a) WIN (b) PRE



(c) TEM (d) GST



(e) SSD (f) PRS



(g) RHU

Fig. 15 Monthly relationship between gaseous pollutants and meteorological parameters

GST ($R=0.868$), and SSD ($R=0.887$). When the temperature increases, it is beneficial to accelerate the photochemical reaction rate in the troposphere, promote the conversion rate between O_3 precursors,

Table 4 Summary of correlation values between gaseous pollutants and meteorological parameters based on monthly and seasonal data in 2014–2020

Pollutants	WIN	TEM	RHU	PRE	SSD	GST	PRS
Yearly							
SO_2	-0.320	-0.371	0.070	-0.303	-0.227	-0.363	0.440
NO_2	-0.058	-0.578	0.216	-0.448	-0.400	-0.553	0.559
CO	-0.405	-0.646	0.379	-0.462	-0.555	-0.637	0.704
O_3	0.522	0.873	-0.722	0.540	0.887	0.868	-0.875
Spring							
SO_2	-0.348	0.011	0.622	0.186	-0.683	0.797	0.932
NO_2	0.831	0.317	-0.348	0.164	0.294	-0.594	-0.606
CO	-0.039	0.338	0.369	0.116	-0.448	0.825	0.803
O_3	0.068	-0.106	-0.582	-0.442	0.625	-0.696	-0.764
Summer							
SO_2	-0.184	-0.323	0.367	0.109	-0.153	-0.196	0.779
NO_2	0.856	0.348	-0.571	-0.247	0.678	0.848	0.264
CO	-0.133	-0.728	0.593	0.208	-0.436	-0.601	0.395
O_3	0.183	0.369	-0.501	-0.897	0.252	0.330	0.008
Autumn							
SO_2	-0.136	0.625	-0.045	0.544	0.044	0.10	0.417
NO_2	-0.032	0.036	-0.142	-0.321	-0.210	-0.217	-0.694
CO	0.097	0.716	-0.342	0.422	0.056	0.195	0.151
O_3	0.234	0.665	-0.171	0.255	0.893	0.840	0.506
Winter							
SO_2	-0.389	-0.044	0.006	-0.280	0.282	-0.403	0.907
NO_2	0.656	0.231	-0.413	0.259	0.655	0.220	0.147
CO	-0.180	-0.021	-0.132	-0.224	0.434	-0.351	0.897
O_3	0.124	-0.408	0.444	0.845	0.425	-0.293	-0.103

and then promote the generation of O_3 (Jeong & Park, 2013; Mousavinezhad et al., 2021; Wang et al., 2019a, 2019b). Studies have illustrated that when there is sufficient sunshine, the strong solar ultraviolet radiation is very beneficial to the photochemical reaction to generate O_3 (Zhao et al., 2018a). Besides, a significant anticorrelation can be found between O_3 and TEM in winter, indicating that the concentration of O_3 was lower in winter because of lower temperature and higher PM concentration, which reduced the photochemical rate of O_3. Furthermore, in winter when the sunshine duration is low, the structure of the atmosphere is stable, which is slow down the spread of pollutants, resulting in high concentrations of other pollutants except O_3 (Lu et al., 2022a, 2022b).

The variation of SO_2, NO_2, and CO were basically consistent with the trend of RHU and PRS, showing a "U" shape (Fig. 15). Furthermore, they also presented a positive correlation with PRS and RHU (Table 4). On the contrary, O_3 were significantly negatively correlated with RHU ($R = -0.722$) and PRS ($R = -0.875$), which is same as the observes of He et al., (2017), who pointed out that O_3 concentration was negatively correlated with relative humidity over China (He et al., 2017). It is possible that under low pressure conditions, the subsidence airflow in the middle and low layers can easily form a static and stable weather pattern, resulting in the accumulation of regional O_3 pollutants near the surface.

4 Conclusions

This research systematically analyzes the annual, seasonal, and monthly variation characteristics of air pollutants and meteorological factors, discusses the main pollutant sources, and finally explore the relationship between pollutants and their relationship with multi-scale meteorological conditions in detail. The main conclusions as follows:

(1) From 2014 to 2020 the concentrations of SO_2, PM2.5, PM10, and CO reduced by 66.67%, 49.23%, 45.92%, and 38.89%, respectively. On the contrary, the concentrations of O_3 and NO_2 showed different upward trends, and there was a complex "seesaw" phenomenon between O_3 and PM. Besides, PM, SO_2, and NO_2 showed a "U-shaped" seasonal variation trend, and O_3 showed an "inverted U-shaped."

(2) The PM2.5/PM10 ratio is high (about 0.65), and NO_2/SO_2 is increasing year by year, indicating that PM2.5 accounts for a large proportion of particulate matter in Chongqing and mobile sources like vehicle exhaust emissions contribute more to pollution than stationary sources such as power generation and coal combustion.

(3) During the study period, SO_2, NOx and dust emissions all showed a significant downward trend, dropping by 90.62%, 58.52%, and 59.22% respectively. Industrial emissions are the main contributor to pollutant emissions, accounting for 81.84%, 58%, and 80.10% of SO_2, NOx and dust emissions, respectively.

(4) The correlation between PM2.5 and PM10 was strong ($R = 0.98$). PM showed a significant negative correlation with O_3 and showed a significant positive correlation with other gaseous pollutants (SO_2, NO_2, CO). Furthermore, O_3 was only negatively correlated with RHU and PRS, but positively correlated with other meteorological factors. In addition, there are certain seasonal heterogeneity in the correlation between pollutants and meteorological factors, indicating that pollution control needs to consider seasonal differences.

Overall, this study still has some shortcomings. For example, the data used in the analysis is the daily average data, and more accurate hourly data can be used for subsequent analysis. Secondly, this study only discusses the temporal variation trends of pollutants and meteorological factors, and the spatial differences and changes of pollutants and meteorological factors at each site can be further explored in the future. In addition, the next step will be to further study the sensitivity between O_3 and precursors (NOX and VOCs).

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Author Contribution All authors contributed to the study conception and design. Data collection and analysis were performed by Xiaoju Li. The first draft of the manuscript was written by Xiaoju Li and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability Data openly available in a public repository.

Declarations

Ethics Approval Not applicable. My manuscript does not report on or involve the use of any animal or human data or tissue.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

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