

Article

Characterization of Spatial and Temporal Variations in Air Pollutants and Identification of Health Risks in Xi'an, a Heavily Polluted City in China

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Abstract: The study of the temporal and spatial characteristics of air pollutants in heavily polluted cities is extremely important for analyzing the causes of pollution and achieving a viable means of control. Such characteristics in the case of Xi'an, a typical heavily polluted city in Fenwei Plain, China, have remained unclear due to limitations in data accuracy and research methods. The monthly, daily, and hourly patterns of O₃ and particulate matter (PM_{2.5} and PM₁₀) are analyzed in this study using on-site data provided by an urban air quality monitoring network. The analysis of variance (ANOVA) method was used to compare differences in pollutant concentrations during different seasons and time periods. The spatial distributions of O₃, PM_{2.5}, and PM₁₀ at different time points following interpolation of the air quality monitoring sites have been analyzed. The results show that the O₃ concentration from 12 p.m. to 3 p.m. was significantly higher than that in the morning and evening, and the concentrations of PM_{2.5} and PM₁₀ from 7 p.m. to 10 p.m. were significantly higher than those in the morning and afternoon. The number of qualified days for PM_{2.5} was less than 30 and unqualified days for O₃ was more than 100 in 2019. There is a potential risk of exposure to pollution with associated health risks. Even on the same day, the spatial pollutant distributions at different time points can differ significantly. This study provides a scientific basis for reducing O₃ and particulate matter exposure. Outdoor activities in the morning in summer are more beneficial to reduce O₃ exposure, and outdoor activities should be curtailed in the evening in winter to reduce particulate exposure. This study provides a scientific basis for the government to formulate public health policies to reduce pollution exposure from outdoor activities.



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Keywords: air pollution; analysis of variance; spatial interpolation; temporal and spatial characteristics; health risk

1. Introduction

Air pollution is caused by human activities and natural processes that discharge certain substances into the atmosphere, endangering human health and welfare when reaching a sufficient concentration that is time dependent [1]. Anthropogenic emissions originate mainly from industrial production and transportation [2,3]. Common air pollutants in cities include particulate matter (PM₁₀), fine particulate matter (PM_{2.5}), and ozone (O₃). Various pollutants have a concomitant impact on urban spaces [4,5]. The superposition of different health hazards caused by different types of pollution has led to an increasing incidence rate and mortality [6]. These hazards include damage to the human respiratory and cardiopulmonary systems caused by O₃, low fertility, respiratory diseases, and arteriosclerosis caused by PM_{2.5} [7–11]. The key to preventing and controlling pollution requires a full understanding of the spatial and temporal characteristics of air pollutants to effectively reduce public exposure to pollution and improve the quality of public life.

Xi'an is located in the western part of the fault basin of the Fenwei Plain, which has been identified as a key area for national air pollution prevention and control by the Ministry of Ecology and Environment of the People's Republic of China [12]. As the only provincial capital city in the Fenwei Plain, Xi'an has the largest population affected by severe pollution. Coal and coking industries are clustered in the Fenwei Plain, which is surrounded by mountains on all sides. An anti-cyclonic airflow stagnation area is readily formed in the plain area because of the blocking effect of the mountains and the sinking of a leeward slope airflow. Due to the significant impact of ground aggregation, pollutants do not easily disperse after aggregation. The combined effect of pollutant emissions from cities in the plain is obvious [13,14]. The frequent hazy conditions in winter affect the mental health of the inhabitants, and the population is exposed to unbearable air conditions [15]. Pollutants pose a threat to public health, leading to increasing medical expenses, which seriously impact the economic development of the region [16,17]. As Xi'an has the largest population and the most developed economy in Fenwei Plain, an analysis of the spatial and temporal pollutant characteristics can inform the prevention and control of pollutants in other cities.

This study assumes significant differences in pollutant concentrations in time and space. The objective of this study is to analyze the monthly, daily, and hourly patterns of O_3 and particulate matter ($PM_{2.5}$ and PM_{10}) and to investigate the temporal differences and spatial distribution characteristics of pollutant concentrations. Five stations were first selected to study the monthly and daily concentration changing characteristics of O_3 , $PM_{2.5}$, and PM_{10} in Xi'an in 2019. The hourly characteristics of O_3 , $PM_{2.5}$, and PM_{10} in five typical polluted days were analyzed using the trend change analysis method, and the temporal characteristics of each pollutant were studied. The analysis of variance (ANOVA) method was used to compare differences in pollutant concentrations in different seasons and time periods. Two time points, 7:00 a.m. and 3:00 p.m., were selected in the analysis of five typical O_3 polluted days (3–7 August 2018) along with three time points, 7:00 a.m., 12:00 p.m., and 6:00 p.m., for five typical PM polluted days (2–6 January 2019). The inverse distance weighting (IDW) method was used to interpolate the pollutant data from 209 stations to obtain the spatial distribution of different pollutants at different time points in the central urban area. Changes in the spatial characteristics of air pollution in Xi'an were assessed using horizontal and vertical comparisons. This analysis provides a scientific basis for air pollution control and prevention in Xi'an, which will reduce public exposure to pollution and improve the environmental health quality of the residents. The structure of this study includes an introduction, methods, results and discussion, and conclusions.

2. Methods

2.1. Region Researched

Xi'an is an important city in the western region of China with a total area of 10,108 km². It has an east-to-west length of ca. 204 km and a north-to-south width of ca. 116 km. The total central urban area of Xi'an is 610.14 km², according to the central city scope delineated in *Xi'an Overall Plan (2008–2020)* [18]. The scope and location of the city's territory and the central urban area are illustrated in Figure 1. Xi'an is located in the western part of the fault basin of the Fenwei Plain, which is one of the most air-polluted areas in the country. According to the national air quality for January to December 2018 reported by the Ministry of Ecology and Environment, Xi'an ranked 158th of 169 cities suffering serious air pollution [12]. In summer, the temperature in Xi'an is high, and radiation is strong, facilitating O_3 generation. Thus, the concentration of O_3 remains high. In Xi'an from 2014 to 2017, the number of unqualified days in terms of O_3 concentration in summer increased from 8 to 61 [19]. There is serious air pollution in Xi'an in both winter and summer.

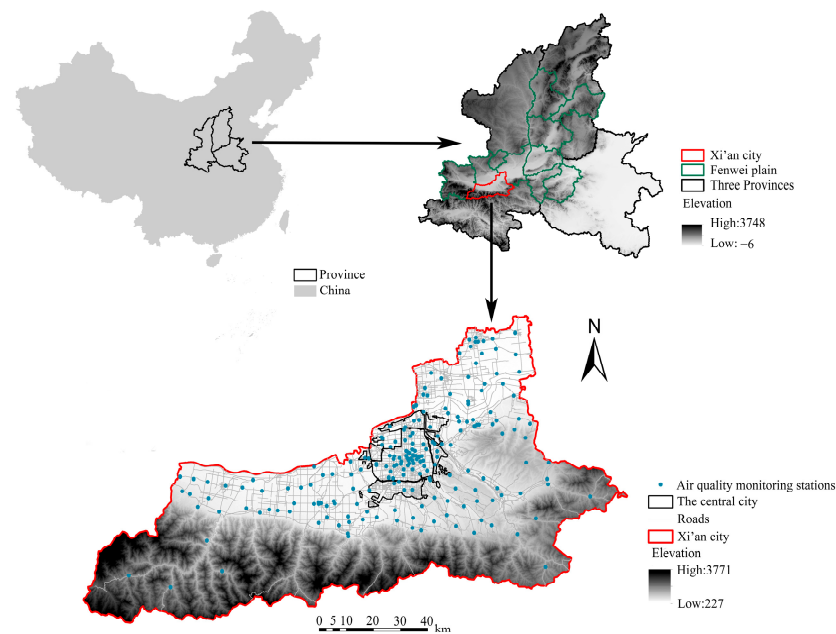


Figure 1. The location of Xi'an and the scope of the research.

2.2. Source of the Data

The air quality data were provided by the Xi'an air quality automatic monitoring network. There are 209 national standard three-parameter air quality monitoring stations; the locations are shown in Figure 1. The three parameters are PM_{10} , $PM_{2.5}$, and O_3 . The average concentrations of $PM_{2.5}$ and PM_{10} are reported hourly and daily, while that of O_3 is reported hourly and daily (a maximum of 8 h). The $PM_{2.5}$ and PM_{10} concentrations are measured using a laser scattering method with a range of $0.01\text{--}2000\text{ }\mu\text{g}/\text{m}^3$, a resolution of $0.01\text{ }\mu\text{g}/\text{m}^3$, and an indication error of $\pm 10\%$. O_3 is measured using an electrochemical method with a range of $0\text{--}500\text{ ppb}$ and an indication error of $\pm 10\%$. Stations used to analyze temporal changes in atmospheric pollutants are based on data completeness and represent different zones.

2.3. The Analysis of Variance (ANOVA) Method

ANOVA was used to compare the differences in the concentrations of O_3 , $PM_{2.5}$, and PM_{10} in different seasons (March–May in spring, June–August in summer, September–November in autumn, and December–February in winter) and different outdoor activity periods (6–9 a.m., 12–3 p.m., 7–10 p.m.). The formulas are provided below:

$$F = \frac{SSB/(k-1)}{SSE/(N-k)} \quad (1)$$

$$SSB = \sum_{i=1}^k n_i (\bar{X}_i - \bar{X})^2 \quad (2)$$

$$SSE = \sum_{i=1}^k \sum_{j=1}^{n_i} (X_{ij} - \bar{X}_i)^2 \quad (3)$$

where F is the statistic, SSB is the sum of squares between groups, SSE is the sum of squares of the residuals, k is the number of groups, N is the total sample number, $\bar{X}_i$ is the mean of the i -th group, n_i is the sample size of the i -th group, and X_{ij} is the j -th sample in the i -th group.

2.4. Inverse Distance Weighted (IDW) Interpolation Method

The spatial interpolation method was used to study the spatial and temporal changing characteristics of air pollutants in the interior space of the city based on the high-density stations of the urban air quality monitoring network. ArcGIS is a desktop application

geographic information system platform that integrates many functions, such as spatial data display, editing, query retrieval, statistics, report generation, spatial analysis, and advanced mapping. Surface interpolation is an ArcGIS tool that creates continuous (or predicted) surfaces based on sampling points. Inverse distance weight interpolation (IDW) is a surface interpolation method that can determine the pixel value through a linear weight combination of a set of sampling points. The weight is an inverse distance function, and the assumption is that the mapped variable can be reduced due to the influence of the distance on the sampling position. The closer the interpolation point is to the known point, the greater the weight. The IDW method has been used in this study as it exhibits more advantages in retaining the original value of the monitoring stations, and the resultant interpolation results are smoother than those generated using other interpolation methods. The formulas are provided below:

$$Z = \frac{\sum_{i=1}^n \frac{1}{(D_i)^p} Z_i}{\sum_{i=1}^n \frac{1}{(D_i)^p}} \quad (4)$$

$$D_i = \sqrt{(X - X_i)^2 + (Y - Y_i)^2} \quad (5)$$

where Z is the estimated value of the interpolation point. The coordinates of Z are set to (X, Y) . The actual value of the i -th data point is set to Z_i , and its coordinates are (X_i, Y_i) . D_i is the distance from the interpolation point to the i -th data point, and p is the power of the distance from the interpolation point to the i -th data point.

3. Results and Discussion

3.1. Daily Pollutant Patterns

A comparison of the ambient air quality standard GB-3095-2012 released by China in 2012 and the global air quality standard AQG2021 updated by the WHO in 2021 is provided in Table 1 [20,21]. China's ambient air functional areas are divided into two categories. The first category includes nature reserves, scenic spots, and other areas that require special protection. The second category encompasses residential areas, commercial and civil-military mixed areas, cultural areas, industrial areas, and rural areas. The Class 1 concentration limit values in Table 1 apply to the first category, while the Class 2 concentration limit values apply to the second category. The Class 2 concentration limit values in China are the same as the Stage 1 WHO target values.

Table 1. Comparison of pollutant index limits for China GB-3095-2012 and WHO AQG2021.

Pollutant	Index	GB-3095-2012		AQG2021				AQG
		Class 1	Class 2	Stage 1	Stage 2	Stage 3	Stage 4	
PM _{2.5} (µg/m ³)	Annual average	15	35	35	25	15	10	5↓
	24-h average	35	75	75	50	37.5	25	15↓
PM ₁₀ (µg/m ³)	Annual average	40	70	70	50	30	20	15↓
	24-h average	50	150	150	100	75	50	45↓
	Peak season	-	-	100	70	-	-	60
O ₃ (µg/m ³)	Daily maximum 8-h average	100	160	160	120	-	-	100
	1-h average	160	200	-	-	-	-	-

↓ Indicates a value below the standard. - Indicates none.

In Table 2, the average daily values of PM_{2.5}, PM₁₀, and O₃ (for a maximum of 8 h) for China and those generated by the WHO were used as criteria to determine the number of unqualified days for pollution at the 5 stations in Xi'an for 365 days in 2019. China uses the Class 2 concentration limit, while the WHO applies the final Air Quality Guideline (AQG) in Table 1. The air quality reported by the Daiwang Street Office (Station 1) and Xiliu Street Office (Station 4) in the suburbs is better than that reported by the Hansenzhai Street

Office (Station 2), Taoyuan Street Office (Station 3), and Caotan Ecological Industrial Park (Station 5) in the central urban area, according to the Chinese standard. Applying the WHO standard, the number of qualified days for $PM_{2.5}$ at the 5 stations was less than 30, the number of unqualified days for O_3 was more than 100, and the number of qualified days for PM_{10} was less than 100 with the exception of Station 1. These data suggest a potential risk of exposure to pollution with consequent health risks [7,8]. The daily variations in O_3 , $PM_{2.5}$, and PM_{10} concentrations are illustrated in Figures 2–4. The black dotted lines in the figures demonstrate that the air quality in Xi'an is still far from the AQG of the WHO.

Table 2. Number of unqualified/qualified days for the pollutants over 365 days in 2019.

Station	Unqualified Days for O_3		Unqualified/Qualified Days for $PM_{2.5}$		Unqualified/Qualified Days for PM_{10}	
	>160 ($\mu g/m^3$)	>100 ($\mu g/m^3$)	>75 ($\mu g/m^3$)	≤ 15 ($\mu g/m^3$)	>150 ($\mu g/m^3$)	≤ 45 ($\mu g/m^3$)
Station 1	4	126	64	27	32	108
Station 2	40	127	75	14	48	65
Station 3	30	117	85	9	65	66
Station 4	19	107	96	28	79	77
Station 5	48	104	69	28	67	56

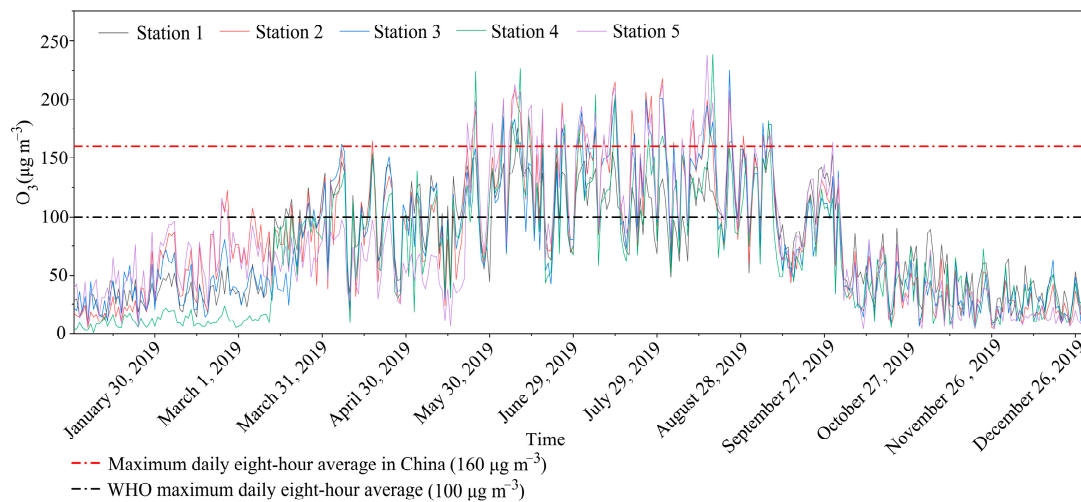


Figure 2. Variation in daily O_3 concentration in Xi'an in 2019.

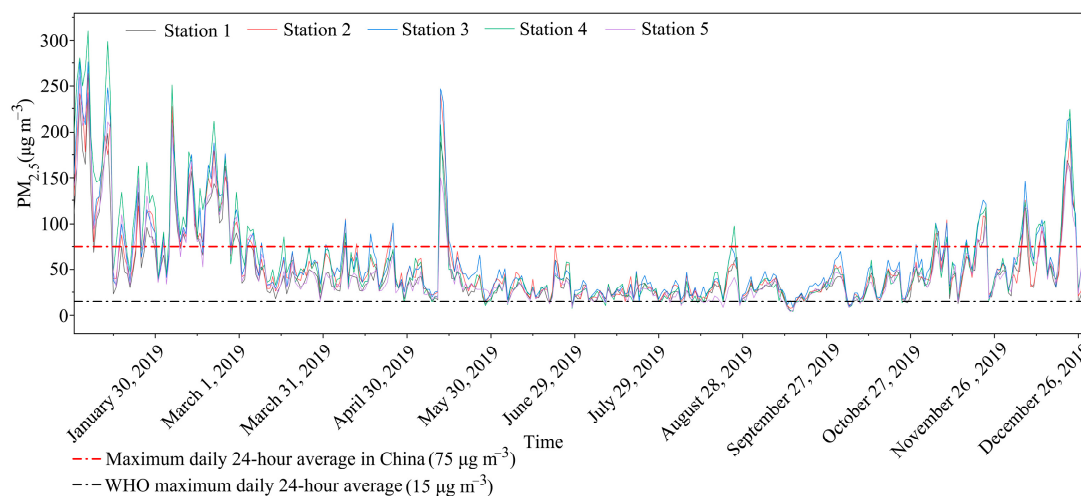


Figure 3. Variation in daily $PM_{2.5}$ concentration in Xi'an in 2019.

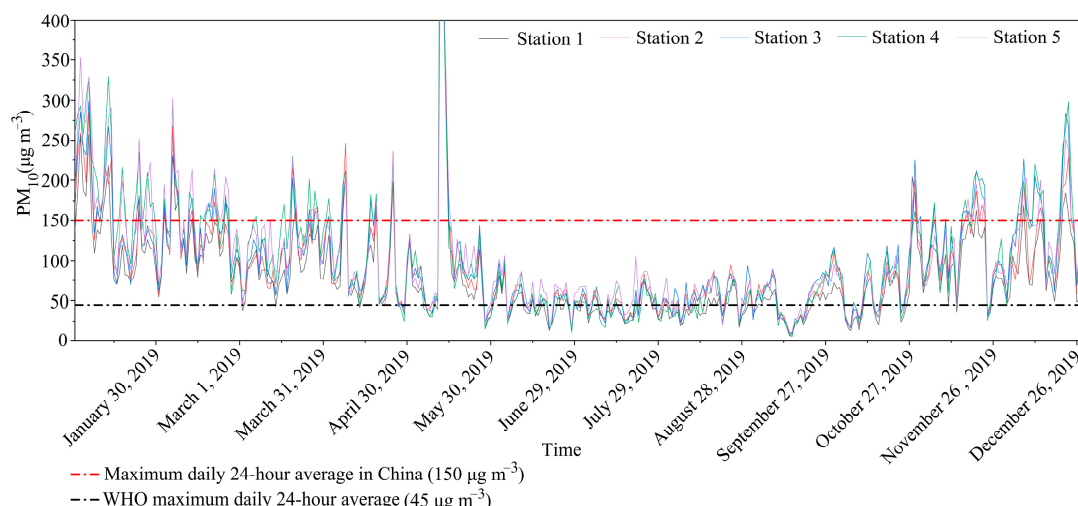


Figure 4. Variation in daily PM_{10} concentration in Xi'an in 2019.

3.2. Hourly Pollutant Patterns and Time Period Differences

3.2.1. Hourly O_3 Concentrations and Time Period Differences

Data from the five air quality monitoring stations allowed a comparison of the 24-h O_3 concentrations on five consecutive typical polluted days (3–7 August 2018). The five stations selected in this instance are different from the five stations used to analyze the monthly pollutant patterns. We chose the monitoring stations on the basis of data integrity and a representation of different locations. The selected stations include Laodian Town (Station 6), Caotan Ecological Industrial Park (Station 7), Liyang Street Office (Station 8), Changle Middle Road Street Office (Station 9), and Xiaozhai Road Street Office (Station 10). It can be seen from the entries in Table 3 that the amplitude (daily maximum minus daily minimum) of O_3 concentration over 24 h recorded by the five monitoring stations on the 5 consecutive days ranged from 62 to 343 $\mu g/m^3$. The O_3 concentration reported by the same station on the same day varied widely within the 24-h period, as revealed in Figure 5. A low concentration level was a feature of the 0:00 to 8:00 a.m. period, with a discernible increase at 9:00 a.m., maintaining a high concentration level from 1:00 p.m. to 6:00 p.m. to reach the peak value. The concentration of O_3 decreased at later times following the peak.

Table 3. Variation in the amplitude (daily maximum minus daily minimum) of the O_3 concentration ($\mu g/m^3$) at 5 monitoring stations over 5 days.

Monitoring Station	3 August	4 August	5 August	6 August	7 August	Average Value for 5 Days
Station 6	220	194	215	193	201	205
Station 7	107	228	246	203	239	205
Station 8	62	132	233	109	103	127
Station 9	130	308	262	343	238	256
Station 10	138	279	259	325	240	248

The results of ANOVA were used to analyze the differences in O_3 concentrations during the three outdoor activity periods (6–9 a.m., 12–3 p.m., and 7–10 p.m.). The results showed that the O_3 concentration in the afternoon was significantly higher than that in the morning and evening ($p < 0.001$ ***), and the O_3 concentration in the evening was significantly higher than that in the morning ($p < 0.001$ ***), as revealed in Figure 6a. This response is closely related to changes in temperature, where a higher temperature enhances the rate of photochemical reactions generating more O_3 [22–24]. To reduce exposure to O_3 , outdoor activities should be curtailed in summer afternoons, and outdoor activities should be conducted as late in the evening as possible.

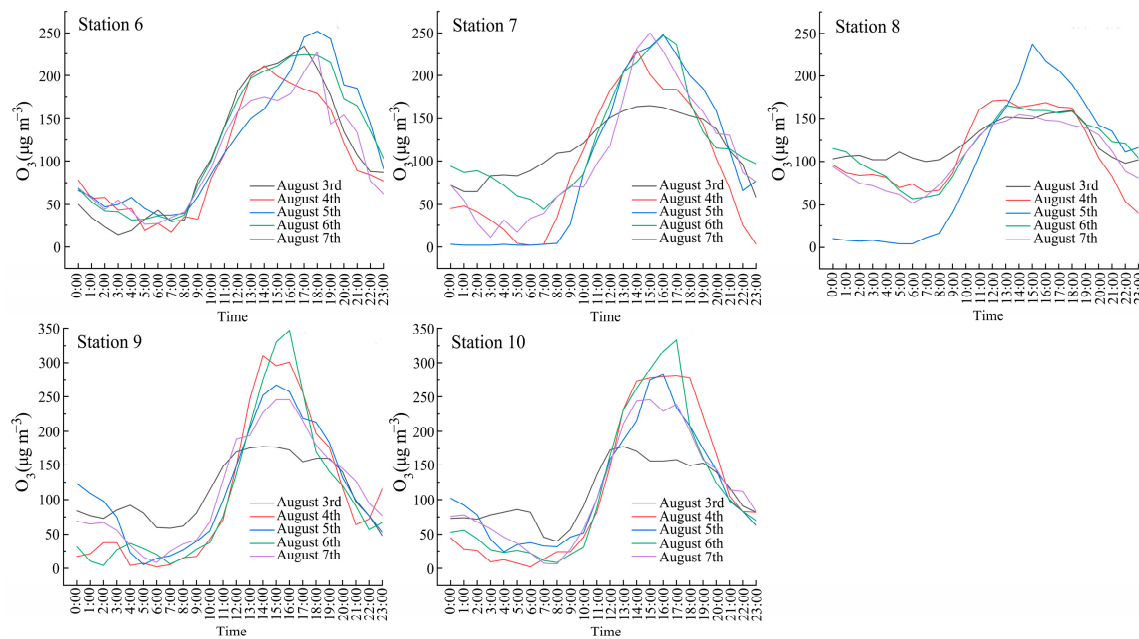


Figure 5. Variation in hourly O_3 concentrations at the 5 monitoring stations over 5 consecutive days.

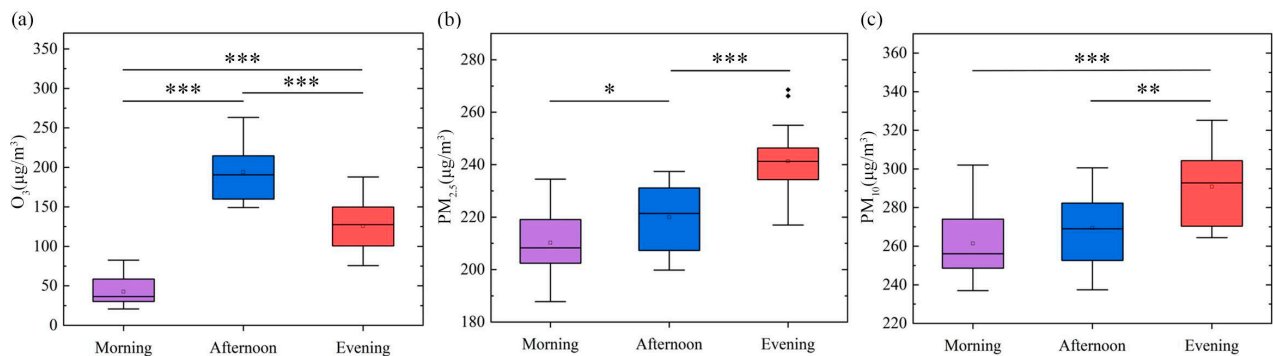


Figure 6. Time period differences in (a) O_3 , (b) $PM_{2.5}$, and (c) PM_{10} concentrations on five consecutive typical polluted days. Significance levels are indicated by asterisks: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

3.2.2. Hourly $PM_{2.5}$, and PM_{10} Concentrations and Time Period Differences

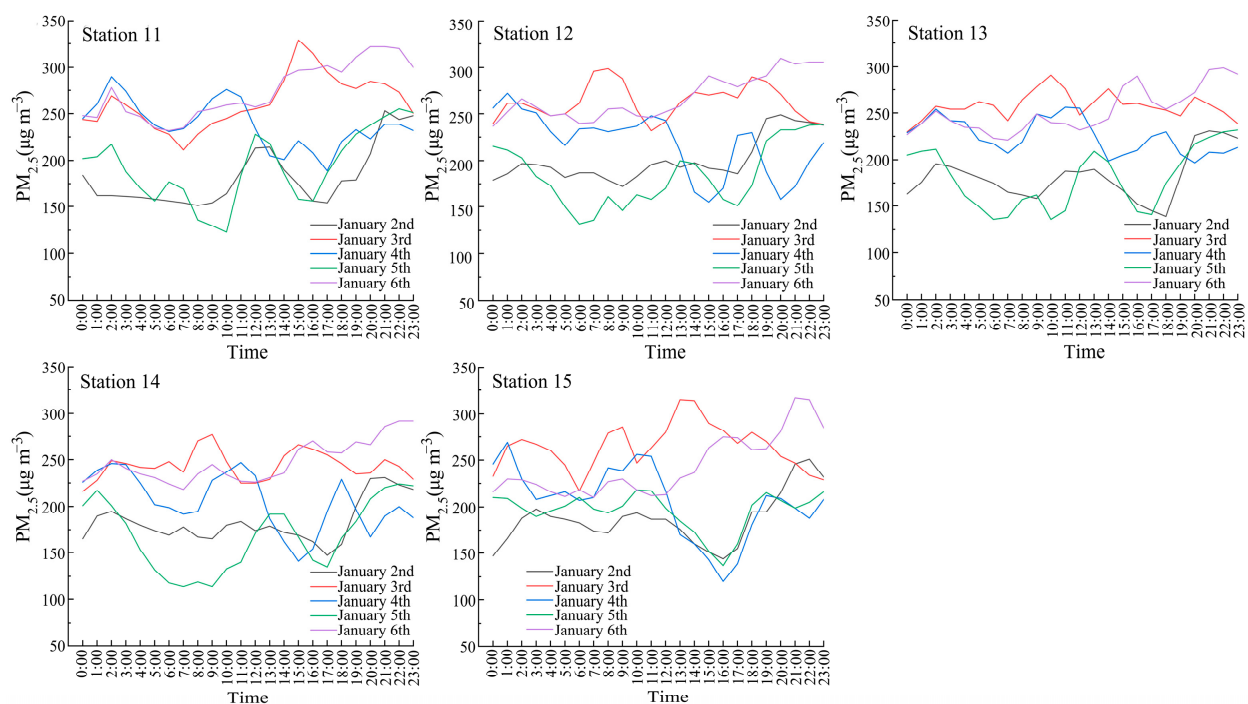
Five air quality monitoring stations were selected to compare the changes in the 24-h concentrations of $PM_{2.5}$ and PM_{10} over five typical pollution days (2–6 January 2019). The selected stations include Headquarters Economic Park Station (Station 11), Chang'an Road Street Office (Station 12), Daming Palace National Heritage Park (Station 13), Xiyi Road Street Office (Station 14), and North High-speed Railway Station (Station 15). It can be seen from Tables 4 and 5 that the range of $PM_{2.5}$ (daily maximum minus daily minimum) over this period is 61–149 $\mu\text{g}/\text{m}^3$, and that of PM_{10} is 61–181 $\mu\text{g}/\text{m}^3$. The concentrations of $PM_{2.5}$ and PM_{10} at the same site changed appreciably within 24 h on the same day. As shown in Figures 7 and 8, there is no discernible consistent pattern in the $PM_{2.5}$ and PM_{10} values, which differs from the O_3 data, and the high and low pollutant concentrations at each station within 24 h also varied widely on different days. The complex variation in $PM_{2.5}$ and PM_{10} concentrations may be due to multiple factors, including uncontrollable emission sources, regional transport of pollutants, and meteorological conditions [22,25].

Table 4. Variations in the amplitude (daily maximum minus daily minimum) of the PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) at 5 monitoring stations over 5 days.

Monitoring Station	2 January	3 January	4 January	5 January	6 January	Average Value for 5 Days
Station 11	102	108	101	132	90	109
Station 12	77	67	117	107	73	88
Station 13	92	61	59	96	78	77
Station 14	84	61	106	110	74	87
Station 15	107	98	149	81	107	108

Table 5. Variations in the amplitude (daily maximum minus daily minimum) of the PM₁₀ concentration ($\mu\text{g}/\text{m}^3$) at 5 monitoring stations over 5 days.

Monitoring Station	2 January	3 January	4 January	5 January	6 January	Average Value for 5 Days
Station 11	134	94	99	120	147	119
Station 13	96	92	100	105	88	96
Station 15	105	69	77	91	76	84
Station 12	105	77	97	130	181	118
Station 14	153	131	156	111	117	134

**Figure 7.** Hourly variations in PM_{2.5} concentrations at the 5 monitoring stations over 5 consecutive days.

The differences between PM_{2.5} and PM₁₀ concentrations in the three outdoor activity periods (6–9 a.m., 12–3 p.m., and 7–10 p.m.) were analyzed using ANOVA, and the results showed that the concentrations of PM_{2.5} and PM₁₀ at night were significantly higher than those in the other two periods, as revealed in Figure 6b,c. Thus, reducing outdoor activities at night in winter could effectively reduce PM_{2.5} and PM₁₀ exposure.

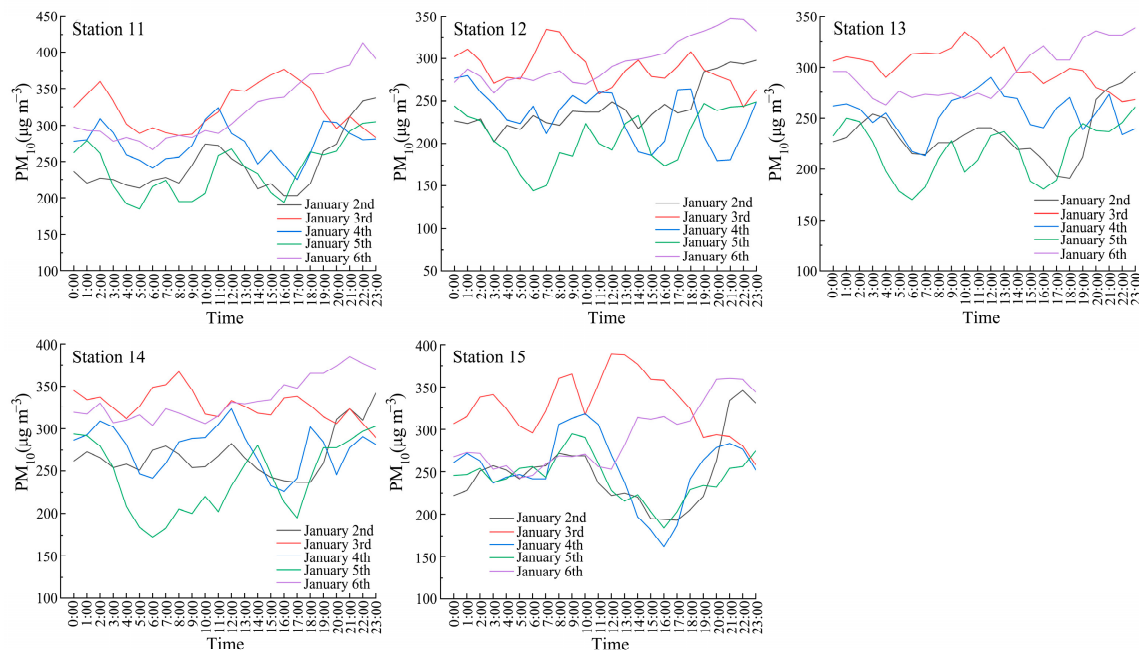


Figure 8. Hourly variations in PM_{10} concentrations at the 5 monitoring stations over 5 consecutive days.

3.3. Monthly Pollutant Patterns and Seasonal Differences

Five air quality monitoring stations in Xi'an were selected to assess the monthly changes in O_3 , PM_{10} , and $PM_{2.5}$. The daily average concentration value was used to calculate the monthly average concentration values for the 12 months in 2019. It can be seen from the entries in Figure 9a that the concentration of O_3 first increased and then decreased in the period from January to December 2019, with the highest value occurring in July. In Figure 9b,c, the concentrations of $PM_{2.5}$ and PM_{10} exhibited an initial decrease and subsequent increase in the same period, with the highest value noted in January.

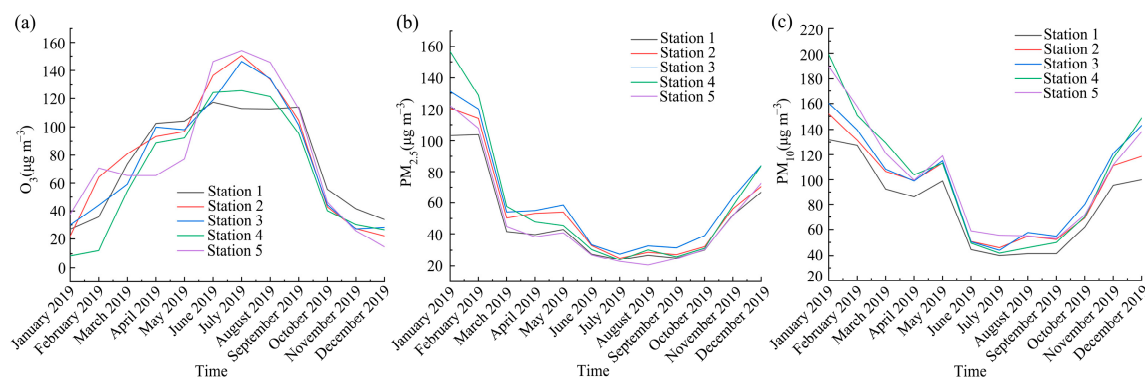


Figure 9. Monthly average concentrations of (a) O_3 , (b) $PM_{2.5}$, and (c) PM_{10} in 2019.

The concentrations of O_3 , PM_{10} , and $PM_{2.5}$ in spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) in Xi'an were analyzed using analysis of variance. The results showed that the concentration of O_3 in summer was significantly higher than that in other seasons ($p < 0.001$ ***), and the concentration of O_3 in spring was significantly higher than that in autumn ($p < 0.001$ ***) and winter ($p < 0.001$ **), as revealed in Figure 10a. This finding can be attributed to the higher temperature in summer, which accelerates the photochemical reactions that generate O_3 [24,26]. The analysis results of $PM_{2.5}$ and PM_{10} were similar, and the concentrations of $PM_{2.5}$ and PM_{10} were significantly higher in winter than in other seasons ($p < 0.001$ ***) and significantly higher in spring and autumn than in summer ($p < 0.001$ **), as revealed in

Figure 10b,c. Given the appreciable pollution caused by winter heating in Xi'an, coupled with the unfavorable terrain and static weather, these pollutants cannot be diffused [27,28].

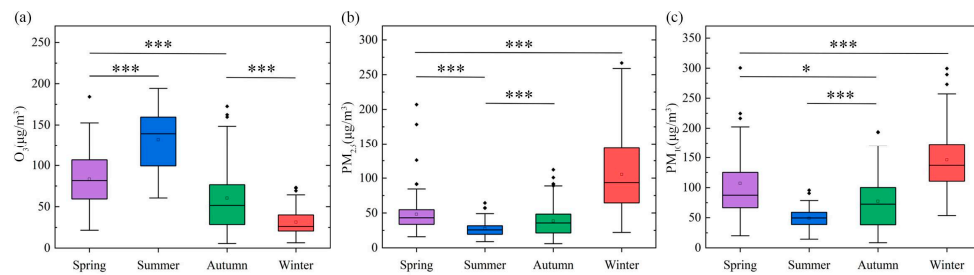


Figure 10. Seasonal differences in (a) O_3 , (b) $PM_{2.5}$ and (c) PM_{10} concentrations in 2019. Significance levels are indicated by asterisks: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

3.4. Spatial Patterns at Different Time Points

3.4.1. Differences in O_3 Spatial Distribution

Two time points, 7:00 for low concentration and 15:00 p.m. for high concentration, were selected for the 5-day period (3–7 August 2018). The daily average O_3 concentration data were used and interpolated as raster data, applying IDW with Arcgis 10.4. The raster data were extracted after interpolation according to the mask (central urban area) to obtain the O_3 spatial distribution for the central urban area of Xi'an. As shown in Figure 11, with the exception of the high O_3 concentration in the middle of the central urban area at 7:00 a.m. on 5 August, the concentration of O_3 in the northern part of the central urban area was much higher than that in other areas on the remaining four days. This serves to indicate that there were emission sources in the northern part of the central urban area that had not been effectively controlled [19,29]. Moving from 7:00 a.m. to 15:00 p.m. (Figure 12), there is no longer evidence of a high concentration of O_3 in the north of the central urban area, and this apparently had shifted to the middle of the central urban area. This can be ascribed to excessive emission of O_3 precursors, such as NO_x and volatile organic compounds, from the dense pedestrian and vehicular traffic in the central urban area [30,31].

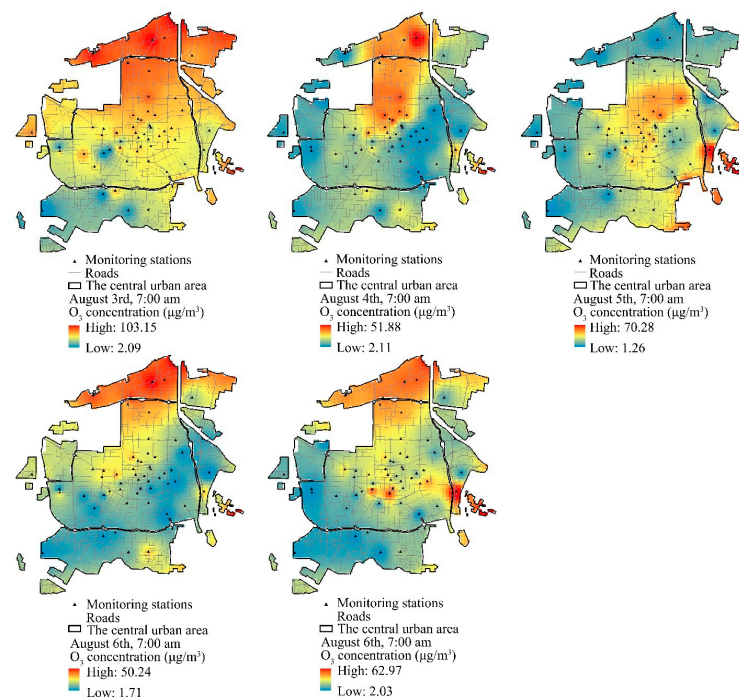


Figure 11. Spatial distribution map of O_3 at 7:00 a.m. in the central urban area from 3 August to 7 August 2018.

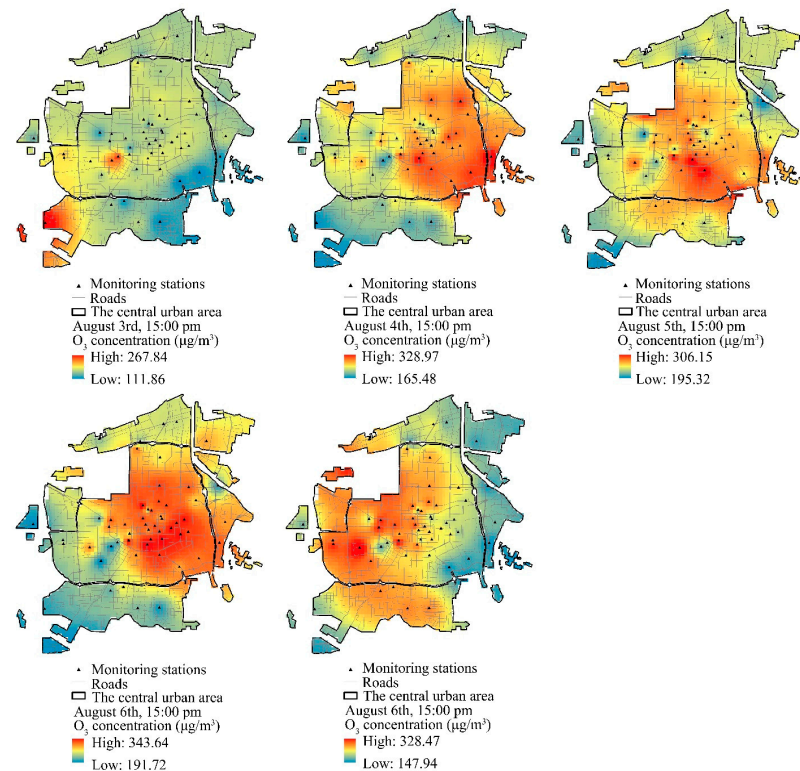


Figure 12. Spatial distribution map of O_3 at 15:00 p.m. in the central urban area from 3 August to 7 August 2018.

3.4.2. Differences in $PM_{2.5}$ and PM_{10} Spatial Distributions

Three time points, 7:00 a.m., 12:00, and 18:00 p.m., were selected for five typical polluted days (2–6 January 2019), representing the morning, noon, and evening peaks, respectively. The spatial distributions of $PM_{2.5}$ and PM_{10} were obtained using the same method as noted for O_3 . The differences in the spatial $PM_{2.5}$ concentration distribution on different days are shown in Figures 13–15. A comparison of the vertical images reveals differences in the spatial $PM_{2.5}$ concentration distribution at different time points on the same day. Differences for different days at the same time point are illustrated in Figures 16–18. Likewise, a comparison of the vertical images establishes differences in the spatial PM_{10} concentration distribution at different time points on the same day. An assessment of the horizontal images shows that $PM_{2.5}$ and PM_{10} at the same time point also differ in terms of spatial distribution. However, in some areas, the concentration remained consistent for the 5-day period. For example, the concentrations of $PM_{2.5}$ and PM_{10} in the west and southwest of the central city were consistently high, while in the southeast, these concentrations were uniformly low. The spatial distributions of $PM_{2.5}$ and PM_{10} show obvious differences at different time points, but there are clearly high-concentrated areas [12,32]. Both the difference and consistency should be recognized and taken into account in developing a pollution control strategy.

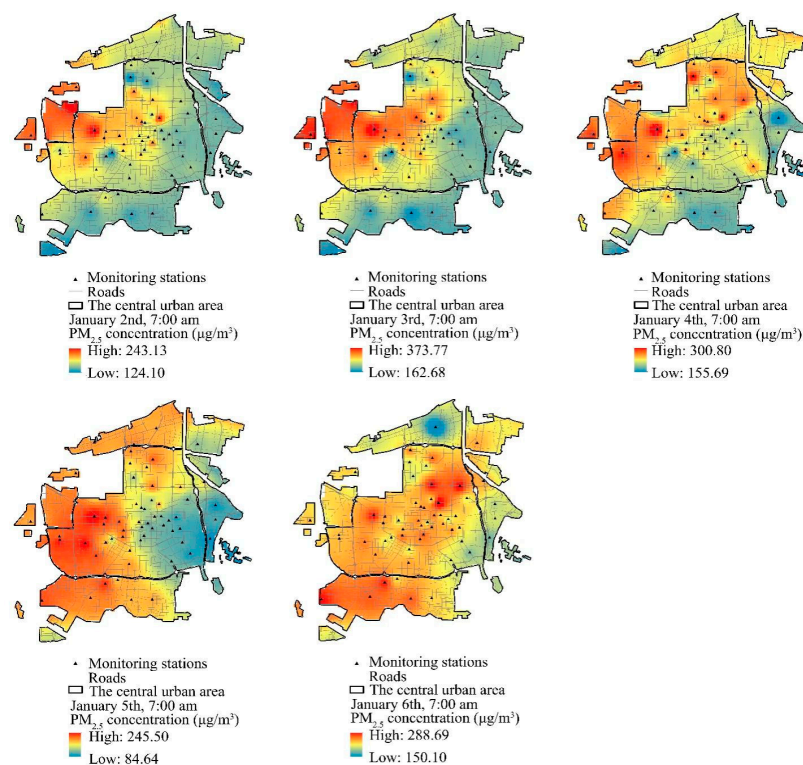


Figure 13. Spatial distribution map of $PM_{2.5}$ at 7:00 a.m. in the central urban area from 2 January to 6 January 2019.

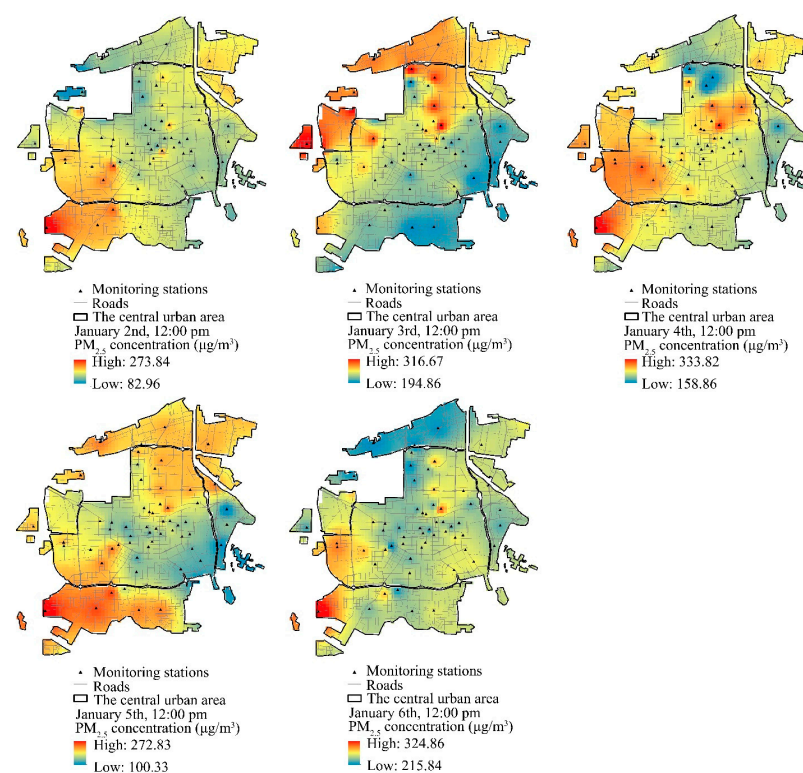


Figure 14. Spatial distribution map of $PM_{2.5}$ at 12:00 p.m. in the central urban area from 2 January to 6 January 2019.

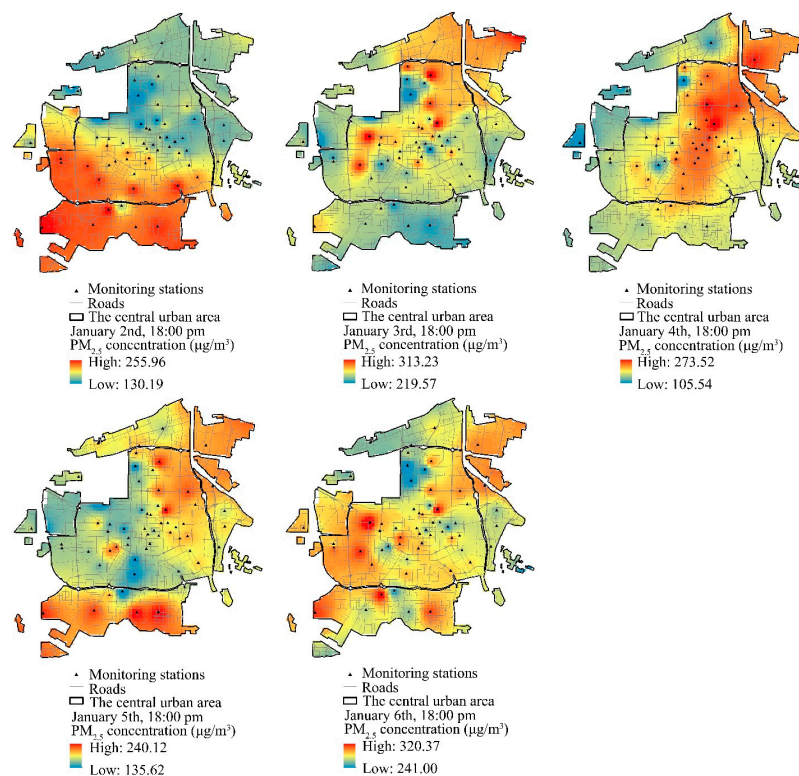


Figure 15. Spatial distribution map of $PM_{2.5}$ at 18:00 p.m. in the central urban area from 2 January to 6 January 2019.

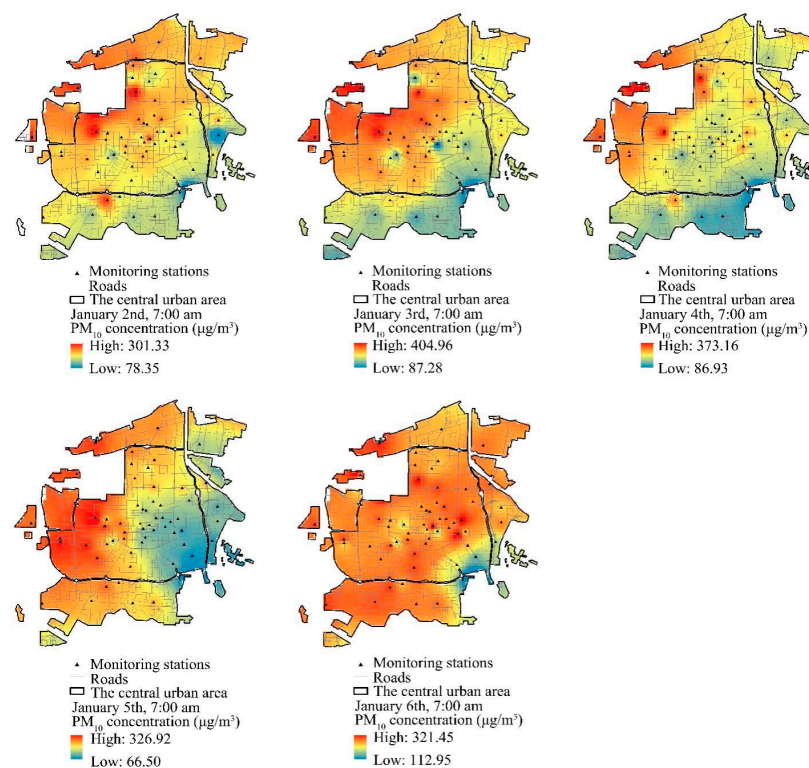


Figure 16. Spatial distribution map of PM_{10} at 7:00 a.m. in the central urban area from 2 January to 6 January 2019.

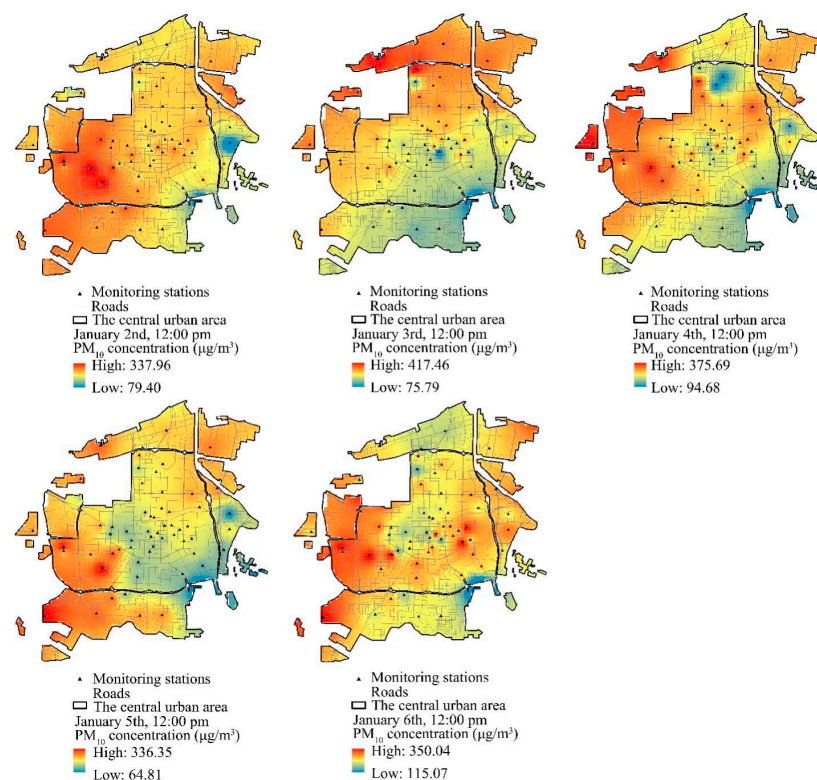


Figure 17. Spatial distribution map of PM_{10} at 12:00 p.m. in the central urban area from 2 January to 6 January 2019.

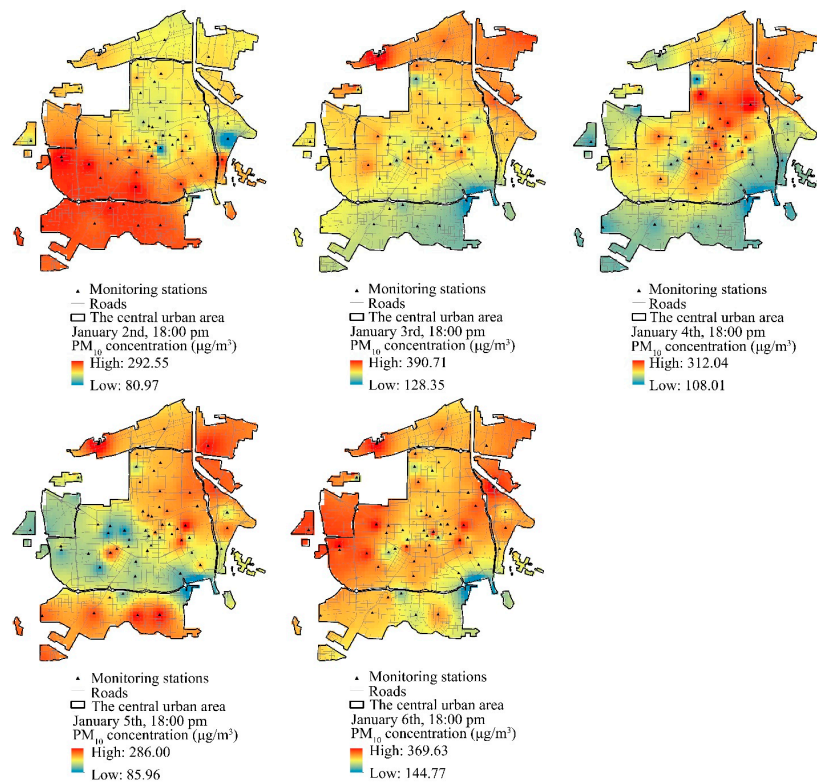


Figure 18. Spatial distribution map of PM_{10} at 18:00 p.m. in the central urban area from 2 January to 6 January 2019.

3.5. Application and Limitation

This study found that the hour-by-hour concentration change in O_3 showed a consistent pattern of change with time as it was high at noon and low in the morning and evening. Thus, the government's governance of O_3 pollution should be strengthened during the high-temperature hours for VOC emission source control. In the morning, low-temperature hours in the northern part of the central city form a high spatial concentration of O_3 . In the afternoon, the high spatial concentration of O_3 shifted to the central part of the central city. The government's policies should pay attention to the regional differences in the emission sources of VOCs and develop a targeted governance program. The hour-by-hour concentration changes in $PM_{2.5}$ and PM_{10} do not show a consistent pattern of time change, and the governance regarding $PM_{2.5}$ and PM_{10} should maintain the long-term nature of the policy. The spatial distributions of $PM_{2.5}$ and PM_{10} at different points in time also show differences, but there are still persistent areas of high concentrations located in the western and southwestern parts of the central city. The treatment of these areas is crucial. To reduce pollution exposure from outdoor activities, the government can issue health reminders. These reminders should indicate that O_3 remains at high concentrations in the evening in summer and declines slowly, and outdoor activities should be postponed as much as possible. In addition, outdoor activities should be carried out in the morning in winter when evenings exhibit more severe $PM_{2.5}$ and PM_{10} pollution than early mornings. Due to the limitations of the workload and the length of the article, we only selected 2–3 representative time points to analyze the spatial distribution of pollutants, and subsequent studies will analyze the spatial distribution of pollutants at more time points and on more days to reveal more patterns of change in the spatial distribution of air pollutants.

4. Conclusions

The temporal and spatial distribution characteristics of O_3 , $PM_{2.5}$, and PM_{10} in Xi'an, a heavily polluted city in Fenwei Plain, were analyzed. Changes to monthly, daily, and hourly concentrations and spatial distributions as well as the differences in concentrations during different seasons and at different time periods have been considered for typical polluted days. O_3 concentrations reflect the prevailing temperature with lower values at lower temperatures (7:00 a.m.) and higher concentrations at higher temperatures, i.e., 15:00 p.m. in summer. In winter, $PM_{2.5}$ and PM_{10} exhibit a morning peak at 7:00 a.m. that dropped during periods of lower traffic flow (12:00), with an evening peak at 18:00 p.m. in winter. The results generated in this study support the following conclusions:

1. The monthly changing pollutant pattern indicates that the O_3 concentration in summer is higher than that in other seasons, with the highest concentration noted in July. The concentrations of $PM_{2.5}$ and PM_{10} in winter are higher than those in other seasons, with the highest concentrations noted in January. ANOVA results show that due to the high temperatures in summer, the photochemical reaction rate of O_3 increases, leading to significantly higher O_3 levels in summer compared to other seasons. Additionally, in winter, the heating and stable weather conditions in Xi'an hinder pollution dispersion, resulting in $PM_{2.5}$ and PM_{10} concentrations being significantly higher in winter than in other seasons.
2. The daily changing pollutant pattern indicates less than 30 qualified days for $PM_{2.5}$ in Xi'an in 2019, according to the latest air quality standards of the WHO. The number of unqualified days for O_3 was greater than 100. This represents a potential risk of exposure to pollution with associated health risks. The government needs to formulate and implement more stringent air quality control policies, including limiting industrial emissions, strengthening traffic management, and promoting clean energy.
3. The hourly pollutant pattern indicates that the concentrations of O_3 , $PM_{2.5}$, and PM_{10} at the same station varied widely within a 24-h period. O_3 concentrations remained at a low level from 0:00 to 8:00 a.m., increased from 9:00 a.m., and maintained a high level from 13:00 p.m. to 18:00 p.m. when it reached a maximum. In order to reduce exposure to O_3 , outdoor activities should be avoided in the summer on

sunny afternoons. Lower O₃ exposure during outdoor activities occurs in the morning compared with the evening, and outdoor activities should occur as late as possible in the evening. The patterns for PM_{2.5} and PM₁₀ are quite different from O₃ over a 24-h period. The concentrations of PM_{2.5} and PM₁₀ at night are significantly higher than that in the other two periods, so reducing outdoor activities at night in winter can effectively reduce PM_{2.5} and PM₁₀ exposure. To prevent pollution exposure of urban outdoor populations, differentiated health risk alert programs and outdoor activity recommendations should be developed for different seasons, time periods, and types of pollutants.

4. The spatial distribution of O₃ at 7:00 a.m. indicates emission sources in the north of the central urban area that are not effectively controlled. A high O₃ concentration is observed at the middle of the central urban area at 15:00 p.m. It is necessary to suppress the emission of O₃ precursors, such as NO_x and volatile organic compounds, while paying attention to regional differences in emission sources and developing targeted treatment programs. The spatial distributions of PM_{2.5} and PM₁₀ indicate significant differences at different time points, but a constant occurrence of high concentrated areas located in the western and southwestern parts of the central city was noted. The continued management of these areas will significantly improve the air quality in Xi'an. Due to the significant differences in the spatial distributions of O₃, PM_{2.5}, and PM₁₀, the observed differences and consistencies should be taken into account in any pollution control strategy.
5. In the air quality ranking of 168 cities in China generated by the Ministry of Ecology and Environment of the People's Republic of China, Xi'an ranked 165th and 164th in 2022 and 2023, respectively, with the top pollutant in summer being O₃, and the top pollutants in winter being PM_{2.5} or PM₁₀. China's three major heavily polluted regions include the Yangtze River Delta, the Beijing–Tianjin–Hebei region, and the Fenwei Plain, which is represented by Xi'an. Significant air quality improvements have been observed in the Yangtze River Delta and Beijing–Tianjin–Hebei regions. Winter particulate matter management has benefited from regional cooperation and joint prevention and control; industrial and energy structure optimization; enhanced mobile source management; and phased, targeted implementation. Effective measures for controlling summer O₃ include in-depth research on pollution sources and formation mechanisms; the development of non-linear coordinated control strategies for PM_{2.5}, O₃, VOCs, and NO_x; unified deployment; and the establishment of a regional photochemical pollution monitoring network. These measures provide valuable experience for air pollution management in Xi'an.

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