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Research Article

Evolution Characteristic and Source Analysis of Ozone Pollution in a Typical Iron and Steel Industrial City

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Abstract

Analyzing the main control factors of ozone pollution changes is crucial to the formulation of pollution control policies, and how to control the major ozone pollution sources in combination with the characteristics of the city accurately is a hot topic in academic circles. To grasp the ozone pollution characteristics of typical steel industrial cities, this study took Anyang City as an example. On the basis of meteorological observation data and ozone monitoring data, the main control factors and regional pollution source characteristics of ozone pollution in typical steel industrial cities was investigated by using the improved Complete Ensemble Empirical Mode Decomposition with Adaptive Noise and the Comprehensive Air Quality Model with Extensions model. Results show that the relative humidity, temperature, and solar radiation have important effects on the interannual variation of summer ozone in Anyang. Among all pollution sources, the industrial sources are the main source of ozone pollution in Anyang in summer with a contribution rate of 43.2%, followed by traffic sources (25.1%). The regional characteristics of ozone pollution in Anyang in summer are evident, and the contribution of regional transmission is 63.2%, mainly affected by the urban agglomeration in central and southern Henan Province and the urban agglomeration in Shandong and Hebei Province. Conclusions reveale the ozone evolution law and influencing factors of Anyang and provide a reference for the formulation of pollution control strategies in typical steel industrial cities.

Keywords: Ozone pollution, Evolutionary characteristics, Empirical mode decomposition, Source resolution

1. Introduction

In recent years, the global urban ozone concentration has increased every year. Especially in summer, ozone has become the primary factor affecting the air quality of some cities [1]. Ozone is an important product of regional atmospheric composite pollution, and its concentration in the troposphere is regulated by the emissions and proportions of precursors, such as volatile organic compounds (VOCs) and NOx [2, 3]. High concentrations of ozone not only affect crop yields and disrupt ecosystem balance but also endanger human health, causing human respiratory and cardiovascular diseases, etc. The current concern about ozone pollution and the management of ozone precursors is still in its infancy [4, 5]. The causes of ozone pollution formation are complex and influenced by a combination of precursor photochemical reactions, meteorological conditions, and regional transport. Considering the large differences in economic development level and industrial structure among different cities, the ozone generation mechanisms also differ greatly. The control mechanisms of meteorology and precursors on the aggravation trend of urban ozone pollution must be investigated for the development of local ozone control policies.

However, most studies have focused on the analysis of O_3 pollution formation patterns in large cities and attributed the causes of pollution formation mainly to motor vehicle emissions within cities [6, 7]. The results of these studies tend to ignore the impact of industrial air pollutant emissions on O_3 pollution in the process of pollution prevention and control, which is not applicable to industrial cities in northern China, which have heavy industrial background. Therefore, the similarities and differences between the characteristics of ozone pollution in industrial cities and commercial cities and the contribution of different pollution sources, such as motor vehicle exhaust and industrial emissions, to the formation of ozone pollution, which is extremely important for precise ozone control, must be analyzed.

2. State of art

Numerous scholars have investigated the factors and long-term trends of urban-scale ozone pollution control [8-10]. Wu et al. [11] pointed out that relative humidity and sunshine intensity were positively correlated with O_3 concentration, whereas wind speed was negatively correlated with O_3 concentration. Miao et al. [12] investigated the complex relationship between the boundary layer height, weather forcing, regional transport, and heavy pollution in summer and showed that severe O_3 pollution in Beijing usually occurred in the afternoon when the boundary layer height was low and the south/southwest winds were prevalent, whereas O_3 pollution in Shanghai mainly occurred during the southwest warm advection. Wang et al. [13] pointed out that the higher O_3 mass concentration in the core area of the Yangtze River Delta region was related to the change in O_3 generation in the core area with respect to NOx

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sensitivity. Yan et al. [14] studied the long-term trends of ozone pollution in Henan Province from 2015 to 2020, and the results showed that the northern cities with the most serious ozone pollution were mainly in the VOC control area. Qi et al. [15] analyzed ozone pollution in Henan Province in 2017 and found that the main meteorological control factors of ozone varied in different seasons, among which ozone was most correlated with sunshine duration in the northern cities. Yang et al. [16] analyzed ozone and meteorological changes in Anyang City from 2014 to 2017, and the results showed that ozone pollution in Anyang City showed a good correlation with temperature, and ozone in summer was affected by regional transmission in the surrounding areas of Anyang City. Zhao et al. [17] analyzed the implementation effect of the Air Pollution Prevention and Control Action Plan, and the results showed no significant change in ambient NOx concentration, but the maximum daily 8-hour average O_3 concentrations increased, which may cause serious health risks to urban residents. Rovira et al. [18] similarly noted an overall upward trend in O_3 concentrations since 2015, which might be related to the emission of VOCs and NOx pollutants, despite strict clean air action plans by local governments.

Most of the existing studies focus on the analysis of the ozone pollution problem in commercial metropolises or provinces, but only a few focuses on the process of urban ozone pollution in the context of heavy industry. Therefore, on the basis of meteorological observation data and ozone monitoring data, this study analyzed the interannual variation and influencing factors of ozone in Anyang, a typical heavy industrial city with a prominent ozone pollution problem. At the same time, the long-term trend variation of ozone and the main regulatory roles of meteorology and emission were investigated by using the improved Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (ICEEMDAN). Lastly, the WRF-CMAx model was used to analyze the ozone pollution sources accurately from both emission sectors and regions. This study aimed to reveal the ozone variation pattern and influencing factors in Anyang City and provide reference for the development of ozone pollution prevention and control strategies in a typical steel-based industrial city.

The remainder of the study is organized as follows: Section 3 describes the study area， the status of data sources, the study methodology and the construction of the model. Section 4 is the result analysis and discussion, the last section summarizes the study and presents relevant conclusions.

3. Methodology

3.1 Study area and data sources

The concentration data of air pollutants were obtained from state-controlled ambient air quality monitoring stations in Anyang City, with four urban sites (Hongmiaojie [HMJ], Yinxing Xiaoqu [YXXQ], Huanbaoju [HBJ], and Tiefosi [TFS]) and one background control site (Mianyansuo [MYS]). Conventional meteorological monitoring data (temperature, relative humidity, wind speed, etc.) were obtained from the meteorological observatory of Anyang Station. In addition, solar radiation was widely considered to have an important correlation with ozone pollution; thus, solar radiation data from the ERA5 reanalysis data provided by the European Center for Medium-range Weather Forecasts were used in this study.

3.2 Improved Complete Ensemble Empirical Mode Decomposition with Adaptive Noise

The empirical mode decomposition (EMD) method is widely used in the study of long-term trends in air pollution [19, 20], where the original signal is decomposed into multiple internal modal components (IMFs) and a residual by an iterative “screening” process. However, the phenomenon of mode mixing often occurs in EMD, in which oscillations of different scales can appear in one mode and oscillations of the same scale can appear in different modes. The ensemble empirical mode decomposition (EEMD) is an improved method based on EMD, which solves the problem of modal confounding by adding different noises to the original sequence several times; however, the number of IMFs generated varies due to the different noises added, causing difficulties in averaging IMFs. Luo et al. [21] improved EEMD and proposed the improved complete ensemble empirical mode decomposition with adaptive noise, a new method to solve the above problems by adding adaptive noise in different decomposition stages, and successfully applied it to decouple the effects of meteorological factors on $PM_{2.5}$ and assess the concentration trends and seasonal variations.

3.3 Air quality model settings

Meteorological condition in east-central China was simulated by using the mesoscale WRF meteorological model. The initial and boundary conditions were provided by the National Centers for Environmental Prediction, and topographic data were obtained from the United States Geological Survey global topographic and land use data. The physical options used in the model include the Morrison microphysical scheme, the rapid radiation transport model global for long-wave and short-wave radiation, the Unified Noah Land Surface Model, and the Grell–Freitas cumulus parameterization scheme.

In this study, the comprehensive air quality model with extensions version 6.5 (CAMx), a three-dimensional multiscale Eulerian air quality model, was used to simulate the air quality of the study area [22]. Meanwhile, the ozone source apportionment technology (OSAT) module, which comes with CAMx, was used to analyze the ozone sources in Anyang City. This module is mainly based on the categories of emission sources and regional ozone precursor markers to trace their transport transformation processes and quantitatively identify the industrial and regional sources of ozone. Among them, the CB6 and CF mechanisms were used for the gas-phase and aerosol chemical reaction mechanisms, respectively, and the PPM calculation method was chosen for the horizontal advection scheme to invoke the Eulerian inverse iteration method [23]. The map projection in the simulated system used the Lamberto projection with the central latitude and longitude coordinates of 36.10° N, 114.36° E, and set up a double-layer nesting, as shown in Figure 1. The grid resolution of the outermost region (D01) was 36 km * 36 km, and that of the inner layer (D02) was 12 km * 12 km. The base year of this study is 2019. The source emission inventories were obtained from the Multiresolution Air Pollutant Emission Inventory Team of China developed by Tsinghua University, and the emission inventories of biogenic VOCs were calculated using the MEGAN natural source emission inventory. To investigate the contribution of different provinces and cities to ozone pollution in Anyang City, different potential source areas were labeled, including eastern Shandong province, south-central Hebei province, Shanxi province, the cities of

Anyang, Xinxiang, Kaifeng, Zhoukou, Zhengzhou, Xuchang, Pingdingshan, Nanyang, Puyang, and other areas in the simulated region. To resolve the magnitude of the contribution of different emission sectors to the summer ozone in Anyang in 2019, the emission sources of different emission sectors were labeled, including the electric sources, industrial sources, resident sources, traffic sources, and natural sources. The simulation period was from June to August 2019, and the temporal resolution of the simulation was 1 hour.

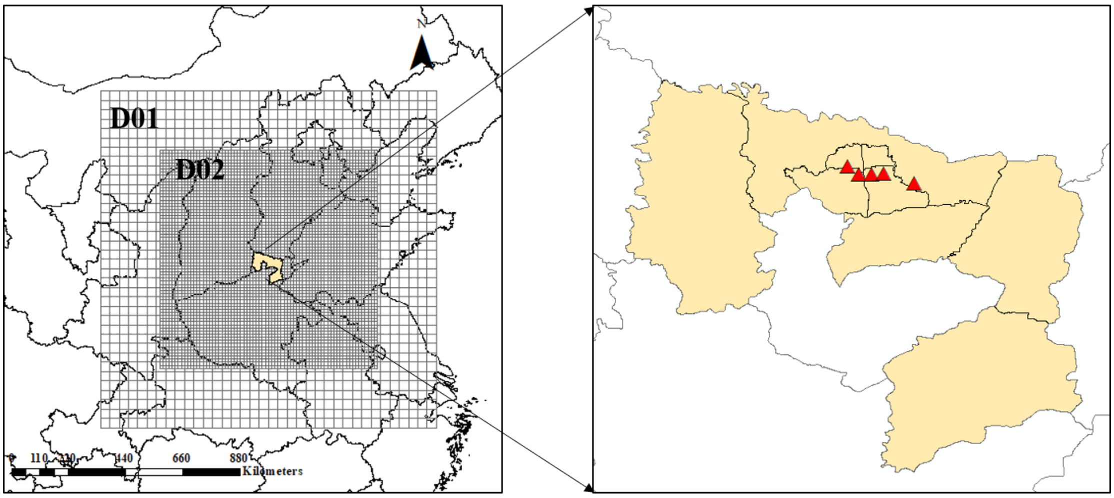


Fig.1. Distribution of model simulation area and observation sites

4. Results and Discussion

4.1 Changes in ozone pollution trends in Anyang City

According to the calculation, the annual average value of O_3 from 2015-2019 showed an overall increasing trend with an annual growth rate of about 8.5 μg/m^3. Figure 2 shows the changes in monthly average O_3 values and seasonal differences in Anyang City from 2015 to 2019.

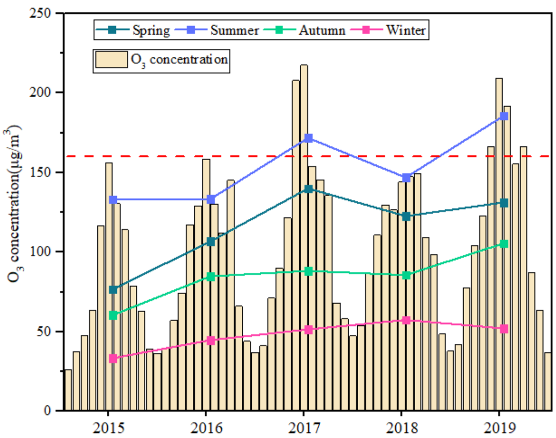


Fig.2. Interannual variation and seasonal differences in ozone pollution in Anyang City (2015–2019)

The most serious period of O_3 pollution in Anyang City occurred in late spring and early summer (May and June), and the most serious pollution was observed in 2017. In terms of seasons, the average O_3 values in Anyang City in all seasons were summer (154.6 μg/m^3) > spring (115.5 μg/m^3) > autumn (85.0 μg/m^3) > winter (47.9 μg/m^3). A certain trend of O_3 growth was observed in all seasons, with the fastest growth rate of O_3 observed in spring and summer; the annual growth rates of O_3 in each season were spring (10.9) > summer (10.5) > autumn (9.0) > winter (3.7). Similar to the results of other scholars, O_3 pollution in Anyang City was the most serious in summer, and the average O_3 values of summer in 2017 and 2019 exceeded the secondary standard (160 μg/m^3) of the Atmospheric Environment Quality Standard.

On the basis of the atmospheric environmental quality standards and monitoring data from five national control stations, the ozone exceedance in Anyang City was statistically analyzed (Figure 3). The average number of ozone exceedance days in Anyang City from 2015 to 2019 showed an increasing trend year by year, from 141 days in 2015 to 242 days in 2019. The changes in the average O_3 concentration on the exceedance days were similar to the changes in the summer O_3 concentration in Anyang City, which also showed a certain degree of increase, with the highest concentrations occurring in 2017 (327.3 μg/m^3) and 2019 (330.2 μg/m^3).

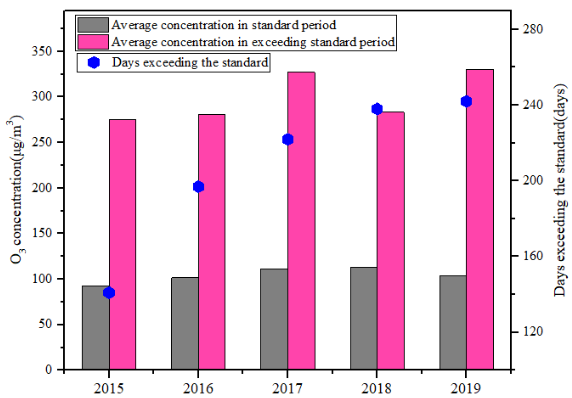


Fig.3. Ozone exceedance in 2015–2019 in Anyang City

4.2 Ozone and meteorological relationships

Meteorological factors, such as temperature, solar radiation, near-surface wind speed, and relative humidity, were considered to have important relationships with O_3-producing transformations [24, 25]. Among them, temperature and solar radiation can contribute to ozone production by promoting photochemical reaction rates. In addition, solar radiation could also accelerate the NO_2 decomposition process and thus promote the increase in ozone concentration. Relative humidity could affect ozone concentration by influencing the processes of light radiation, ozone elimination reaction, and wet deposition, and wind speed mainly affected the process of ozone transport and transformation. Considering the seriousness of summer O_3 pollution in Anyang City, this study combined meteorological element data and O_3 monitoring data to conduct a regression analysis of the factors that might affect the growth of ozone in Anyang City in summer. The results are shown in Figure 4.

In terms of single-month changes, in June, solar radiation and temperature showed a year-on-year upward trend, whereas wind speed decreased year-on-year, and relative humidity showed a downward trend, except in 2015. The meteorological conditions in Anyang City in June shifted in the direction of favoring the formation of O_3 pollution, which also partly explained the fact that O_3 pollution increased in June. Compared with that of other years, the temperature and solar radiation in Anyang City in July 2019 were at a high level, whereas the wind speed and relative humidity were relatively low; the abnormal increase in O_3 in Anyang City in July 2019 confirmed the close relationship between it and meteorological conditions. Overall, the most important meteorological factor affecting the interannual variation of summer O_3 in Anyang City is relative humidity (R=−0.65). In addition, temperature (R=0.52) and solar radiation (R=0.61) also exhibited some correlation. The correlation between near-surface wind speed and interannual variation of O_3 was weak. However, the correlation between meteorological factors and the interannual variation of summer O_3 in Anyang was relatively low and could not fully explain the interannual variation trend of O_3.

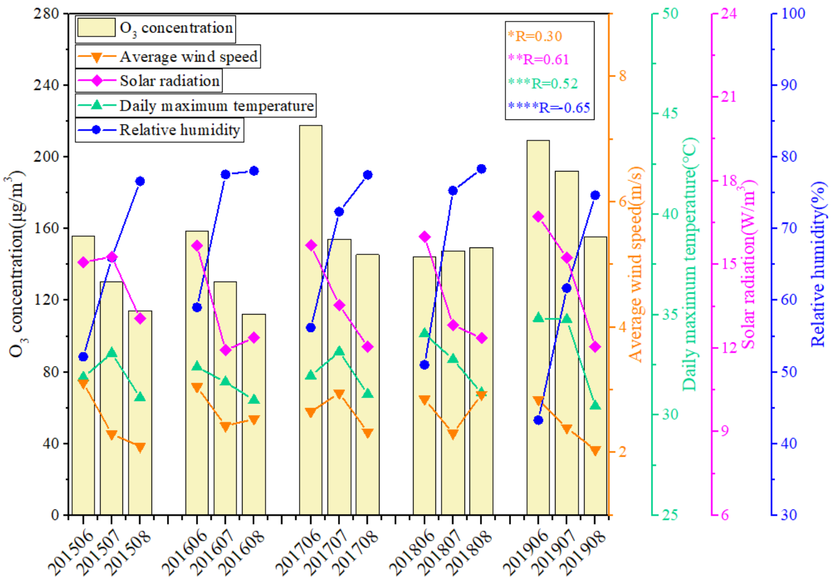


Fig. 4. Interannual variation of summer ozone and related meteorological factors in Anyang City

4.3 ICEEMDAN method for diagnosing changes in ozone trends

The decomposition of ozone monitoring data from five state-controlled stations and meteorological station observation data in Anyang City from 2015-2019 was conducted using the ICEEMDAN method, and the period and variance contribution of different eigenmodal functions were calculated separately. The results are shown in Table 1. Through decomposition, the intra-annual (IMF13), semiannual (IMF12), monthly (IMF10), daily (IMF4) and smaller scale fluctuations of the data at each monitoring station were obtained in this study. Among the monitoring stations, the largest contribution of variance was found for the fluctuations at the period 0.5–0.9 days and intra-annual scales, indicating that ozone has significant intraday and intra-annual (seasonal) variability, which is similar to the results of most studies.

From the decomposition results of the meteorological data, the main cycle of temperature variation occurs at 297.3 days (81.89%), which could be approximated as an annual scale variation. The cycle variation of temperature was consistent with the ozone cycle variation on an intra-annual scale, indicating that temperature was an important factor responsible for the seasonal variation of ozone. The variation of wind speed, on its part, consists mainly of short-period (0.5-2.5 days) fluctuations that match the daily variation of ozone. The variation in relative humidity, which is relatively broad, has fluctuations on a daily to annual scale.

Table 1. Mean period and variance contribution of ozone monitoring data and meteorological element eigenmodal functions (IMF) at each station

Eigenmode functions		YXXQ	TFS	HBJ	HMJ	MYS	Wind speed	Temperature	Relative Humidity
IMF1	Variance contribution rate	0.42%	0.52%	0.47%	0.47%	0.43%	0.38%	0.02%	0.06%
	Period/days	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
IMF2	Variance contribution rate	0.63%	0.71%	0.66%	0.65%	0.70%	2.84%	0.03%	0.17%
	Period/days	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
IMF3	Variance contribution rate	12.20%	13.85%	12.96%	14.18%	13.46%	11.52%	0.26%	2.45%
	Period/days	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.5
IMF4	Variance contribution rate	20.03%	19.70%	14.24%	17.98%	19.75%	23.63%	4.87%	12.24%
	Period/days	0.9	0.9	0.7	0.9	0.9	0.8	0.9	0.9
IMF5	Variance contribution rate	3.28%	3.38%	2.65%	3.15%	3.29%	10.22%	0.38%	3.17%

	Period/days	1.4	1.4	1.2	1.4	1.4	1.4	1.2	1.5
IMF6	Variance contribution rate	2.53%	3.10%	2.22%	2.99%	2.67%	9.06%	0.74%	6.50%
	Period/days	2.3	2.4	2.1	2.4	2.4	2.5	2.1	2.7
IMF7	Variance contribution rate	2.59%	3.10%	2.23%	2.61%	2.21%	6.55%	1.54%	11.88%
	Period/days	4.5	4.7	3.8	4.7	4.4	4.7	4.1	5.4
IMF8	Variance contribution rate	2.06%	2.40%	1.93%	2.13%	1.92%	6.07%	1.88%	7.23%
	Period/days	8.4	9.0	7.2	8.8	8.1	8.5	8.1	10.4
IMF9	Variance contribution rate	2.84%	2.11%	1.51%	2.82%	1.60%	3.44%	1.34%	7.90%
	Period/days	16.7	16.3	14.1	16.6	15.1	16.2	16.4	21.2
IMF10	Variance contribution rate	1.29%	2.26%	2.60%	1.21%	1.84%	2.38%	0.91%	6.00%
	Period/days	32.9	32.3	36.7	33.6	29.2	34.0	32.7	44.9
IMF11	Variance contribution rate	1.35%	1.74%	6.94%	1.64%	1.74%	1.13%	0.63%	5.65%
	Period/days	69.0	72.0	79.0	70.1	57.7	71.5	61.1	89.9
IMF12	Variance contribution rate	27.86%	23.57%	22.02%	31.45%	18.60%	2.22%	81.89%	16.36%
	Period/days	217.1	231.3	149.7	297.9	155.6	151.5	297.3	198.7
IMF13	Variance contribution rate	16.24%	5.60%	20.97%	1.30%	10.76%	4.45%	0.14%	5.63%
	Period/days	339.4	397.0	311.2	404.0	309.4	302.5	440.7	394.0
IMF14	Variance contribution rate	0.61%	/	4.91%	/	0.29%	0.10%	/	1.34%
	Period/days	525.3	/	368.7	/	388.0	451.3	/	520.4
IMF15	Variance contribution rate	/	/	/	/	1.02%	/	/	/
	Period/days	/	/	/	/	724.4	/	/	/

4.4 Ozone trends after removing the influence of meteorological conditions

Near-ground ozone was mainly generated by precursors, such as VOCs and NOx, through photochemical reactions, and controlling the emissions of precursors was an important way to mitigate ozone pollution. However, a nonlinear effect was observed between ozone production, and emission reduction does not necessarily reduce ozone pollution. Part of this is because NOx could have a titration effect with ozone, causing a decrease in ozone concentration. In 2015-2019, Anyang City was mainly in the ozone VOC control area, and its ozone changes were mainly controlled by VOC emissions. With the implementation of emission reduction measures in Anyang City, NOx concentration decreased by about 24% from 2016 to 2019, whereas the changes in VOC emissions from anthropogenic sources were relatively small. To assess the impact of precursor emissions, especially NOx emission reduction, on ozone pollution in Anyang City, this section further analyzed the ozone trends after removing the influence of meteorological conditions based on the IMF results.

Considering that the influence of meteorological conditions on ozone rests nearly on the fluctuations of the intra-annual cycle, the residuals and IMF components larger than the annual scale were superimposed on the basis of the ICEEMDAN decomposition results and the average cycle of each IMF to obtain the trend curve of ozone with the influence of meteorological changes removed. The results can characterize the contribution of emission changes to the interannual variability of ozone, which is shown in Figure 5. After obtaining the ozone change trends after removing the influence of meteorological conditions, the trends were analyzed for significance using the Mann–Kendall method [26], and the results are identified in Figure 5. Among them, two stations, i.e., HBJ and TFS, were not considered during the analysis due to serious missing data.

Both urban sites in HMJ and YXXQ showed a significant increasing trend ($p<0.05$), with ozone increasing by about 15.3% and 26.3%, respectively. The results indicate that in the urban area of Anyang City with a significant reduction of NOx, the titration effect of NO weakened; thus, ozone depletion was reduced, showing a trend of year-on-year growth. Although a certain growth trend (5.2%) was also observed in the ozone after removing the influence of meteorological conditions at MYS, its increasing trend was nonsignificant. Given that the MYS is a background monitoring station far away from the urban area and less influenced by the reduction of anthropogenic source precursors, the correlation with the significant reduction of NOx was weak, and its changes were mainly controlled by the meteorological conditions.

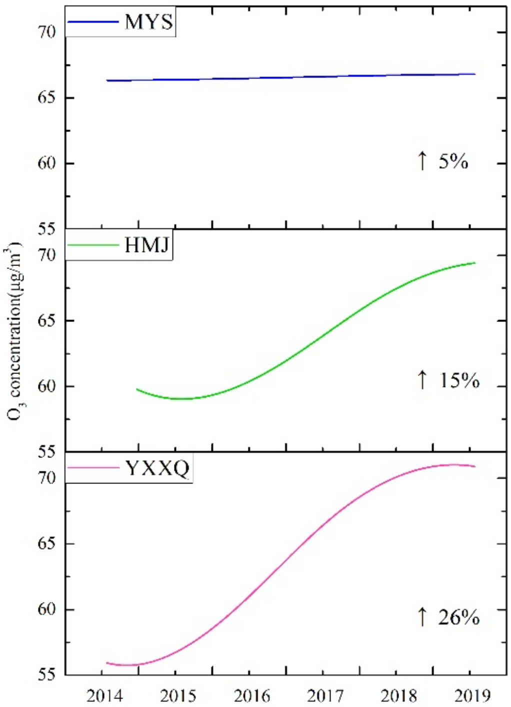


Fig.5. Demeteorization ozone trends by monitoring site in 2015–2019

The contribution of meteorology and emission to the interannual variation of ozone at each monitoring site in Anyang City was quantified by the original time series. The results showed that the annual mean change of ozone at YXXQ, HMJ, and MYS from 2015 to 2019 were 72.6%, 40.3%, and 41.0%, respectively. For the three sites, the contribution of variation due to pollution emissions were 26.3%, 15.4%, and 41.0%, and the contributions of meteorological conditions were about 46.2%, 24.9%, and 35.8%, respectively.

4.5 Evaluation of model simulation results

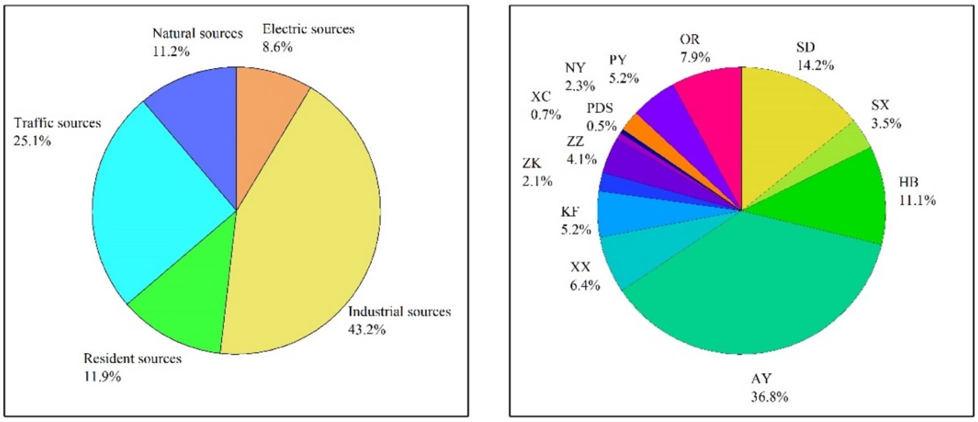
The WRF-CAMx model was used to simulate ozone in Anyang City in summer 2019. The simulation results were evaluated using the air pollutant monitoring data from the national control stations, and the evaluation indexes used were mean deviation (MB), standardized mean deviation (NMB), standardized mean error (NME), root mean square error (MFB), and root mean square deviation (MFE). The results of the simulation validation of pollutants for each month are shown in Table 2. The results showed that the NMB and NME of SO_2 were high, the simulation effect was relatively poor, and the simulation results for other pollutants were within an acceptable range. For the ozone simulation, the hourly ozone concentration and the 8-hour sliding average of ozone were evaluated separately, and the results showed that although the ozone simulation was underestimated, it was relatively small, and MFB and MFE were within the allowable range (−15%<MFB<15%, MFE<35%). Overall, WRF-CAMx in this study could accurately simulate the pollutant concentrations, and the errors in the simulation results were within acceptable limits for further ozone source resolution studies [27, 28].

Table 2. Parameters for evaluation of model simulation results

Contaminants	Month	MB	NMB (%)	NME (%)	MFB (%)	MFE (%)
$PM_{2.5}$ (μg/m^3)	6	5.2	22.4	34.8	11.7	22.8
	7	−1.2	−2.7	29.7	−4.3	21.3
	8	7.8	27.5	47.4	15.7	37.4
PM_{10} (μg/m^3)	6	−6.0	−18.0	54.1	−19.3	45.7
	7	−0.9	−1.6	58.5	0.3	48.1
	8	−12.3	−19.8	55.1	−24.4	56.2
SO_2 (μg/m^3)	6	5.4	6.8	63.2	7.3	80.8
	7	61.3	4.2	54.6	70.6	77.6
	8	4.5	7.8	49.2	66.5	68.0
NO_2 (μg/m^3)	6	1.8	7.1	22.1	12.5	31.1
	7	4.9	12.4	25.4	14.3	23.1
	8	4.3	19.3	32.2	9.2	28.1
CO (μg/m^3)	6	−0.4	−34.3	50.3	−22.1	47.8
	7	−2.5	−25.9	46.1	−25.2	42.2
	8	−0.3	−30.2	40.1	−23.2	41.2
O_3 (μg/m^3)	6	−11.1	−25.4	37.2	−2.9	21.3
	7	−13.2	−30.5	31.2	−8.6	13.2
	8	−7.6	−16.7	21.2	−9.2	22.8
O_3_8h (μg/m^3)	6	−12.8	−13.9	22.3	−10.3	26.6
	7	−4.6	−5.9	26.1	−12.2	31.5
	8	−16.2	−16.2	32.1	−14.9	33.1

4.6 Ozone source analysis results

To analyze the role of pollutant pollution and regional transportation of ozone pollution in Anyang City in summer 2019, the ozone sources were analyzed in this study using the OSAT module in the CAMx model. The results are shown in Fig. 6. In addition, the relative share of each source was statistically analyzed after the normalization. Figure 6(a) shows the industry sources of ozone in Anyang City in summer 2019; the most significant contribution to ozone in Anyang City was from the industrial sources with 43.2%, followed by the traffic sources (25.1%), the residential sources (11.9%), the natural sources (11.2%), and the electric sources (8.6%). As an important industrial production base in Henan Province, the industrial structure of Anyang City, i.e., with metallurgy, building materials, and coal chemical industry as the pillar industries, has been one of the most decisive reasons for the serious ozone pollution. In addition, given the rapid growth of motor vehicle ownership in Anyang in recent years, its contribution to ozone pollution was also becoming increasingly prominent, and pollution prevention and control of mobile sources and oil quality were also necessary.



(a) (b)

Fig.6. Results of ozone source analysis in Anyang City in summer 2019

Figure 6(b) shows the relative proportions of the contributions of different regions to the ozone concentration in Anyang in summer 2019. The ozone pollution in Anyang had a strong regional transport character, which was related to its geographical location in the border area of Hebei, Shanxi, and Henan provinces. In terms of provinces and city groups, ozone pollution in Anyang City mainly originates from local (36.8%), followed by the south-central city group

(26.5%), and the contribution from the western city group of Shandong province (14.2%); the contribution from the south-central city group of Hebei province (1.1%) cannot be ignored either. Among the cities in Henan province, Puyang (5.2%) and Xinxiang (6.4%), which are adjacent to Anyang, contribute the most. In summary, the regional pollution characteristics of ozone in Anyang were evident, and except for the contribution of urban clusters in south-central Henan province, the regional transmission effect of Shandong and Hebei province also had an important influence on summer ozone pollution in Anyang. Therefore, strengthening the regional joint prevention and control between Anyang and the urban agglomeration in south-central Henan province, as well as Shandong and Hebei province, was an important means to manage the summer ozone pollution.

5. Conclusions

Based on meteorological observations and ozone monitoring data, this study took Anyang City as an example to analyze the main regulatory factors of ozone pollution and the characteristics of regional pollution sources in a typical iron and steel industrial city using the improved ICEEMDAN and WRF-CAMx models. The following conclusions were obtained:

(1) Ozone pollution in Anyang City generally showed a rising trend, with an increase rate of 8.5 μg/m3 per year. In addition, the number of ozone pollution days showed a rising trend year by year, and the proportion of ozone exceedance days in Anyang City reached 66% in 2019. Ozone pollution was the most serious in Anyang City in summer.

(2) Changes in summer ozone pollution in Anyang City had a strong correlation with relative humidity, temperature, and solar radiation. The reduction of NOx in Anyang City caused an increase in ozone by 26.3% (YXXQ) and 15.0% (HMJ) from 2015 to 2019, and the contribution of changes in meteorological conditions to changes in ozone trends was 46.2% (YXXQ) and 24.9% (HMJ).

(3) As an important industrial base, the industrial sources contributed most significantly to summer ozone pollution in Anyang, with a contribution of up to 43.2%, followed by the traffic sources (25.1%). The implementation of emission reduction measures for industrial and traffic sources could reduce summer ozone pollution in Anyang. From the regional source analysis results, the regional characteristics of summer ozone pollution in Anyang City were evident, and the contribution of regional transmission was greater than the local contribution; thus, the management of summer ozone pollution in Anyang should strengthen the joint prevention and control between regions.

In this study, the process and characteristics of ozone pollution in Anyang, a typical steel city, were explored and studied in depth. However, given that most cities in northern China have a background of heavy industrial development, not only the steel industry as the mainstay industry. Therefore, the results of this study could not represent all industrial-type cities. To guarantee the accuracy and scientificity of ozone management, further studies on other types of industrial cities are necessary.

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