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Analysis of Ozone Pollution Characteristics and Meteorological Factors in Langfang City From 2013 to 2023

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ABSTRACT
This study systematically analyzed the spatial and temporal distribution characteristics of ozone pollution and its meteorological driving mechanism in Langfang City from 2013 to 2023, and revealed the formation mechanism and evolutionary trends of ozone pollution.The study found that the ozone concentration in Langfang City showed a significant upward trend, the annual average value increased from 95.00 μg/m^3 to 144.17 μg/m^3 and the number of months exceeding the standard increased by 167%. The concentration in summer (June-August) was significantly higher than that in winter, indicating that ozone pollution had obvious seasonal characteristics. Air temperature is the core driving factor for ozone concentration. For every 1°C increase, ozone concentration increases by 6.111 μg/m^3 ($p < 0.001$), while relative humidity exerts an inhibitory effect on ozone formation when controlling for temperature ($B = -1.215$). The multivariate regression model showed that meteorological factors jointly explained 86.7% of the variation of ozone concentration, indicating that meteorological conditions are pivotal in the formation of ozone pollution. It is recommended to prioritize the reduction of highly active VOC_s emission sources during the window period of high temperature and static weather, and quantify the contribution rate of exogenous input through regional transport flux monitoring.

KEYWORDS
Ozone Pollution; Meteorological Factors; Characteristic Analysis; Correlation Analysis

1 Introduction

Langfang City is located in the center of the Beijing-Tianjin-Hebei region and is an important node city for the coordinated development of the region (Xiang Fangfang et al., 2024). Owing to its unique geographical location, the air quality of Langfang City is not only affected by local pollution sources, but also significantly affected by the regional transmission of surrounding cities (such as Beijing and Tianjin). In recent years, with the acceleration of industrialization and urbanization, the problem of air pollution in Langfang City has become increasingly prominent, especially ozone pollution has emerged as a key factor constraining the improvement of air quality (Huang Zijian et al, 2024). Although Langfang City has made some progress in improving air quality (Hu Yuning et al., 2024), the problem of ozone pollution is still severe. Based on the air quality data released by Langfang Environmental Protection Bureau from 2013 to 2023, this study systematically analyzed the spatial and temporal distribution characteristics of ozone pollution and its influencing factors, aiming to elucidate its formation mechanism and evolutionary patterns.This study not only provides a scientific basis for air quality management and policy formulation in Langfang City and even the Beijing-Tianjin-Hebei region, but also offers practical guidance for optimizing pollution control strategies, promoting regional coordinated development, and ensuring public health and ecological security. It has important theoretical value and significant social and environmental benefits.

2 Data Sources and Analysis Methods

2.1 Data Source

The air quality data used in this study are derived from the National Urban Air Quality Real-time Publishing Platform (https://air.cnemc.cn:18007) of China Environmental Monitoring Station. This platform provides monthly air quality data of Langfang City from 2013 to 2023, including the concentration of pollutants such as O_3 and the comprehensive pollution index. The meteorological data are derived from the China Meteorological Data Network (http://data.cma.cn), which covers the meteorological elements such as temperature, relative humidity, wind speed and wind direction during the same period.

2.2 Data Analysis Methods

(1) Descriptive statistical analysis

The descriptive statistics of ozone concentration and related meteorological factors were carried out, and the mean, maximum and minimum values were calculated to understand the basic characteristics and variation range of ozone pollution.

(2) Time distribution analysis

The seasonal and interannual variation characteristics of ozone concentration were analyzed by drawing monthly and annual variation maps of ozone concentration.

(3) Correlation analysis

Pearson correlation coefficient was used to evaluate the linear relationship between ozone concentration and meteorological factors (such as temperature, relative humidity and wind speed), and to identify the key driving factors of ozone pollution.

(4) Multiple linear regression analysis

A multiple linear regression model was constructed to quantify the contribution of each factor to ozone concentration, evaluate its relative importance, and predict the change trend of ozone pollution with ozone concentration as the dependent variable and meteorological elements and precursor concentration as independent variables.

3 Analysis of Ozone Time Distribution Characteristics

3.1 Annual Distribution Characteristics

From 2013 to 2023, the annual average value of ozone concentration in Langfang City increased from 95.00 μg/m^3 to 144.17 μg/m^3 , and the median increased from 69.00 μg/m^3 to 135.00 μg/m^3, indicating that ozone pollution increased year by year. The increase in standard deviation and variance indicates intensified concentration fluctuations, and the instability and uncertainty of pollution are enhanced. The rise in both the minimum and maximum values highlights the severity of pollution, especially in 2017, the maximum value reached 251 μg/m^3. These findings reveal the serious ozone pollution situation in Langfang City and underscore the urgency of implementing effective control measure (Fig.1).

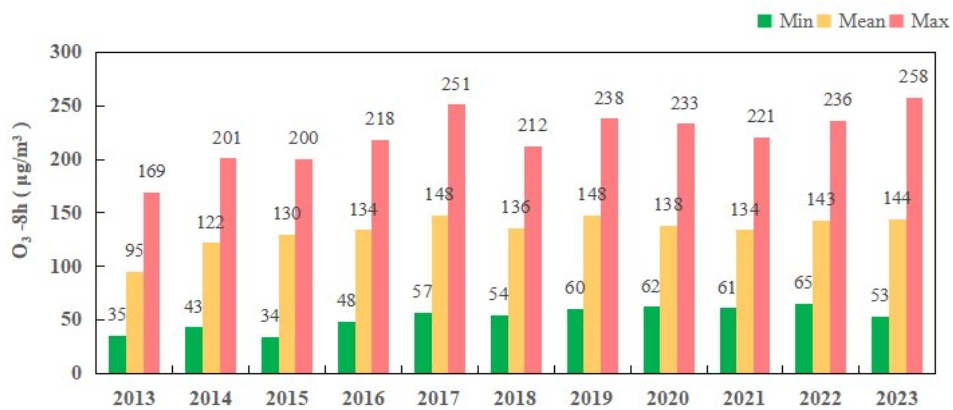

Fig. 1 O_3-8h Distribution Characteristics From 2013 to 2023

3.2 Monthly Distribution Characteristics

According to the data of China Environmental Monitoring Station, in the monthly variation of ozone concentration in Langfang City from 2013 to 2023, the concentration increased significantly in summer (June-August) and decreased in winter (December-February), showing obvious seasonal fluctuations. According to the ' Ambient Air Quality Standard ' (GB 3095-2012), the ozone concentration is limited to 160 μg/m^3. The number of months experiencing mild or worse ozone pollution in Langfang City showed a year by year increase, reaching mild pollution in only 3 months in 2013 and increasing to 8 months in 2023. The number of moderate pollution months also increased, 1 month in 2013 and 3 months in 2023. The number of months with ozone concentration exceeding the standard (> 160 μg/m^3) increased from 3 months in 2013 to 8 months in 2023, indicating a worsening of pollution (Fig 2). These trends highlight the urgency of implementing effective ozone pollution control measures to mitigate their health and ecological impacts.

4 Analysis of the Influence of Meteorological Conditions On Ozone Concentration

4.1 Variable Description

Ozone concentration (O_3-8h) is the dependent variable of this study, indicating the concentration level of ozone in the air. Ozone is a secondary pollutant, which is mainly generated by the photochemical reaction of volatile organic

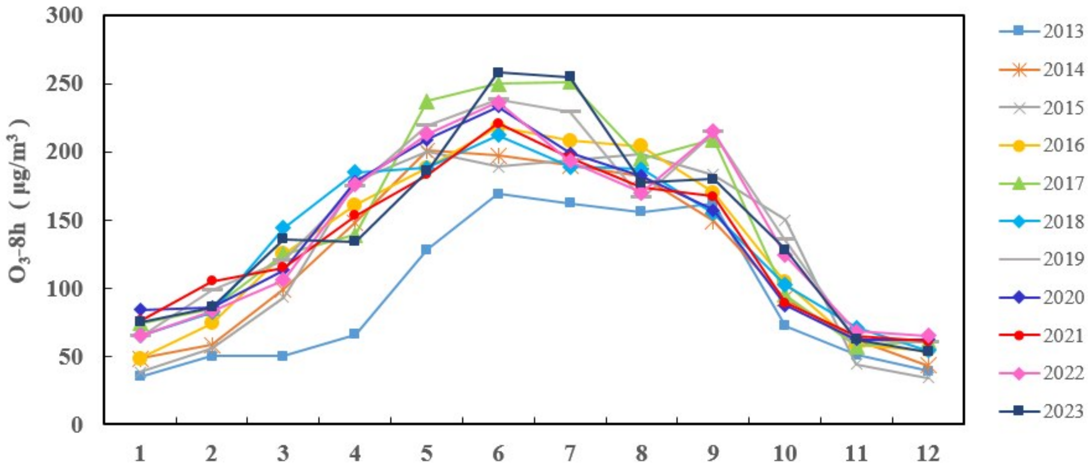

Fig. 2 O_3-8h Monthly Concentration Line Chart From 2013 to 2023

compounds (VOC_s) and nitrogen oxides (NO_x) under sunlight irradiation. The change of ozone concentration is affected by many factors, including meteorological conditions and precursor emissions. Meteorological conditions are important factors affecting ozone concentration. In this study, the following meteorological factors were selected as independent variables : (1) Temperature (Temp, °C) : High temperature conditions accelerate photochemical reactions and promote ozone generation. (2) Relative humidity (RH, %) : Humidity affects the efficiency of photochemical reactions, and ozone is more likely to accumulate under low humidity conditions. (3) Wind speed (WS, m/s) : Wind speed affects the diffusion and dilution of pollutants, and low wind speed is conducive to the accumulation of ozone. (4) Wind direction (WD) : The change of wind direction may bring the influence of regional transmission, and the specific wind direction may aggravate ozone pollution.

4.2 Correlation Analysis

Correlation analysis showed that O_3-8h was significantly positively correlated with temperature (r = 0.915, p30°C), and the formation rate of free radicals (such as OH) was 40% -60% higher than that at room temperature, which directly promotes ozone accumulation. At the same time, the correlation between temperature and humidity (r = 0.514) and wind speed (r = -0.096) showed that the high temperature in summer was often accompanied by regional static weather (wind speed ⩽ 1.5 m/s frequency up to 24%). Such a meteorological combination prolonged the retention time of precursors, resulting in a significant increase in ozone formation potential (OFP).

Although the traditional photochemical model suggests that high humidity may inhibit ozone production, the observed positive correlation between humidity and ozone (r=0.325) in the study area suggests a localized mechanism. Firstly, the reaction pathway of oxygen-containing VOC_s (such as aldehydes and ketones) emitted from Langfang industrial sources with OH radicals is more active at high humidity, which promotes the conversion efficiency of ozone precursors. Secondly, the significant negative correlation between humidity and wind speed (r = -0.542) indicates that the high humidity environment corresponds to the static stability condition, and the diffusion of pollutants is hindered, which aggravates the local accumulation of precursors. In addition, the heterogeneous reaction of secondary aerosols (such as nitrates) under high humidity conditions can release NO_x, which indirectly strengthens the ozone generation chain. Therefore, the interactive effect of wind speed and humidity on ozone concentration are complex and needs to be comprehensively evaluated in combination with other pollution sources and conditions that promote ozone formation (Table 1).

Table 1 Pearson Correlation Analysis Results

Var.	O_3-8h	Temp.	RH	WS
O_3-8h	1	.915**	.325**	-0.041
Temp.	.915**	1	.514**	-0.096
RH	.325**	.514**	1	-.542**
WS	-0.041	-0.096	-.542**	1
WD	0.133	0.139	-0.062	0.014

4.3 Multiple Regression Analysis

The multiple regression model showed that air temperature, relative humidity, wind speed and wind direction jointly explained 87.1% of the variation of daily maximum 8-hour ozone concentration (O_3-8h) in Langfang City (adjusted R2 =

0.867), and the model prediction error was 23.228 μg / m^3 ($F = 213.796$, $p < 0.001$). As the core driving factor, the unstandardized coefficient for temperature is 6.111 ($p< 0.001$), that is, every 1°C increase in temperature leads to an increase in ozone concentration of 6.111 μg/m^3, which confirms that the photochemical reaction rate increases exponentially with temperature. Relative humidity showed an inhibitory effect ($B = -1.215$, $p < 0.001$), and the apparent contradiction with the previous correlation analysis revealed the duality of its mechanism of action : when the temperature was not controlled, the seasonal co-variation of humidity and ozone covered its independent influence ; after introducing temperature variables, high humidity weakens local ozone generation efficiency by promoting aerosol heterogeneous reaction(such as nitrate deliquescence releasing NO_x) and free radical consumption pathways.

Table 2 Multiple Linear Regression Analysis Results

Var.	Unstand. Coeff.		stand. Coeff.	t	P	95.0% CI		VIF
	B	SE	Beta			Down	Up	
con.	140.157	19.051	—	7.357	0.000	102.458	177.857	—
Temp.	6.111	0.231	1.042	26.487	0.000	5.655	6.568	1.519
RH	-1.215	0.221	-0.254	-5.491	0.000	-1.653	-0.777	2.097
WS	-13.198	6.670	-0.078	-1.979	0.050	-26.398	0.002	1.521
WD	-0.279	0.353	-0.026	-0.791	0.430	-0.977	0.419	1.051

The residual analysis diagram of the regression model shows that the standardized residuals show ideal random distribution characteristics in each interval of the standardized predicted values. Specifically, the residual distribution exhibits no clear trend or systematic pattern, which indicates that the conditions of residual independence and mean zero in the model hypothesis are well satisfied. In addition, the distribution range of residuals remains relatively stable at different predictive values, and with no evidence of obvious heteroscedasticity(e. g., 'trumpet-shaped'or'funnel-shaped'distribution) obvious heteroscedasticity is observed, such as ' trumpet-shaped ' or ' funnel-shaped ' distribution, which further supports the assumption that the residual variance of the model is constant. In terms of outlier detection, the absolute value of residuals is mostly concentrated in the standard deviation range of ± 2, and only a few points are close to the boundary of ± 2, but there are no extreme outliers exceeding ± 3. This indicates that the model is reasonably robust to the data, and the influence of outliers on the overall fitting effect of the model is relatively limited. Further observation of the shape of the residual distribution found no obvious curve or bending trend, suggesting that the model's linearity assumption holds for the current dataset, without the need to introduce additional nonlinear terms or variable transformation. On the whole, the residual analysis results of the regression model show that the model fitting effect is ideal, which can better explain the change of dependent variables and meet the basic assumptions of regression analysis (Fig.3).

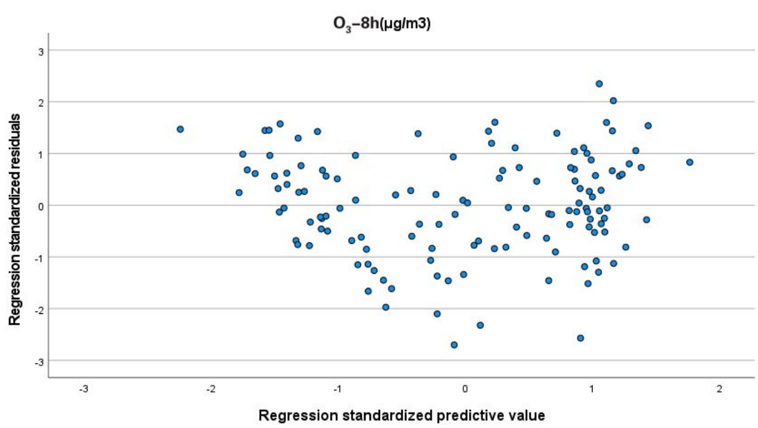

Fig.3 O_3-8h Regression Model Scatter Plot

5 Discussions

5.1 Spatio-Temporal Differentiation and Driving Mechanism of Ozone Pollution

From 2013 to 2023, the ozone pollution in Langfang City showed significant spatial and temporal heterogeneity. The average annual concentration increased from 95.00 μg/m^3 to 144.17 μg/m^3, and the number of months exceeding the standard increased by 167%. The peak concentration in summer (June-August) was 1.6-1.8 times higher than that in winter. As the dominant driving factor, every 1 increase in temperature can lead to an increase in ozone concentration of 6.111 μg/m^3 ($p < 0.001$), which confirms that the photochemical reaction rate increases exponentially with temperature (

Huang Yuzhe et al., 2024). Relative humidity showed an inhibitory effect after controlling the temperature variable (B = – 1.215), revealing the combined effect of aerosol hygroscopic growth promoting free radical consumption and heterogeneous reaction of nitrate releasing NO_x in high humidity environment (Liu et al., 2024). The multivariate regression model showed that meteorological factors jointly explained 86.7% of the variation of ozone concentration, indicating that meteorological factors(temperature, humidity, wind speed, and wind direction) can effectively account for the variations in ozone concentration, and demonstrates strong predictive capability for ozone pollution. and the model has a strong predictive ability for ozone pollution. In addition, meteorological conditions are the core driving factors for the formation and evolution of ozone pollution, especially under the conditions of high temperature, low wind speed and static weather, the accumulation of ozone concentration is particularly significant. However, the variables of precursor emission and regional transport are not included, which leads to the limitations of the model 's explanatory power.

5.2 Refined Governance Path Design

Based on ozone formation sensitivity and meteorological thresholds, a dynamic response mechanism needs to be constructed : in the window period of high temperature and static weather, priority should be given to reducing emissions from industrial solvent use and highly active VOC_s in mobile sources. Based on the PTR-TOF-MS online monitoring network, the emission inventory of aldehyde and ketone species was established, and the key industries such as packaging and printing were controlled. At the same time, we will promote cross-regional transport flux monitoring in the Beijing-Tianjin-Hebei region, quantify the contribution rate of exogenous input, and formulate differentiated ecological compensation schemes.

5.3 Research Limitations and Future Directions

The current model is constrained by insufficient spatial and temporal resolution of emission data, and thus precluding analysis of dynamic effect of diurnal variation of VOC_s components on ozone generation. In the future, WRF-Chem model and observation data should be coupled to quantify the nonlinear influence of humidity on free radical concentration within the meteorological-chemical coupling mechanism.

6 Conclusion

This study systematically revealed the evolution and formation mechanism of ozone pollution in Langfang City from 2013 to 2023. At the theoretical level, the constructed meteorological-chemical coupling model confirms that temperature is the core switching variable of ozone generation which causes a concentration increase of 6.111 μg/m^3 for every 1°C increase. The thermodynamic response, while the humidity shows an inhibitory effect after controlling the temperature (B = -1.215), which subverts the cognitive limitations of traditional single-factor analysis. At the practical level, an integrated governance strategy comprising of ' active species list-meteorological threshold response-regional ecological compensation ' is proposed. The research is limited by the resolution of the regional transport flux monitoring network. In the future, it is necessary to couple the vehicle MAX-DOAS navigation observation with the CMAQ model to quantify the contribution level of exogenous input to local ozone generation, so as to provide more accurate decision support for the joint prevention and control of Beijing-Tianjin-Hebei.

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