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Abstract: Based on Geodetector model, this study adopted the 2016 O_3 concentration data, meteorological factor data and anthropogenic emissions data to explore the driving factors of urban O_3 concentrations in China. The results show that: in general, meteorological factors dominate the urban ozone concentration in China, but there are some differences in the driving factors of ozone concentration at different scales. From the national scale, sunshine duration and temperature are the most significant driving factors, among which temperature is the most critical, while relative humidity and temperature have prominent interactions. From the seasonal perspective, the dominant factors for 3 pollution in spring and winter are the duration of sunshine, the relative humidity in summer, and the temperature in autumn. In addition, the main interaction in spring, autumn and winter is the interaction between sunshine duration and temperature, while in summer it is air pressure and relative humidity. From the perspective of the zoning, the O_3 pollution in South China is dominated by the duration of sunshine, and the other regions are dominated by temperature. In terms of factor interaction, the strongest interactions in Central China, Northeast China, and Southwest China are combined with relative humidity and temperature. East China, North China, and Northwest China are the duration and temperature of sunshine, while South China is the duration of sunshine and wind speed. From the seasonal influence of different zones, the influencing factors of O_3 concentration changes in each region in different seasons are very different. The influence of evaluation factors on this scale is generally not obvious, and the driving factors and interactions are complicated.

Keywords: O_3 concentration; Geodetector model; meteorological condition; anthropogenic emissions precursors; Chinese cities

1 Introduction

O_3 (ozone) in the atmosphere mainly exists in the ozone layer in the lower part of the stratosphere. It absorbs ultraviolet light of a certain wavelength from outer space and protects the earth, including human beings. However, the tropospheric O_3, which is mainly derived from photochemical reactions, is a harmful secondary pollutant. Under continuous accumulation, it not only has a great impact on the human respiratory system, but also endangers human health and can cause the material to fade and age. It affects the growth of plants by affecting the soil, which ultimately affects the ecological environment (Fishman and Crutzen, 1978; Lou et al., 2010; Dong and Li, 2019). The main sources of tropospheric O_3 include natural sources and anthropogenic sources. Natural sources mainly have stratospheric input and photochemical reactions, while the anthropogenic sources are mainly industrial production, electricity supply, residential emissions, transportation and other sources. O_3 precursors such as NOx (nitrogen oxides), VOC (volatile organic compounds), and CO (carbon monoxide) emitted during these production and life processes will undergo photochemical reactions under certain environmental conditions to form O_3 (Pan et al., 2016).

At present, China's O_3 pollution is becoming more and more serious, and O_3 has already occupied the second place in China's urban air pollutants, second only to particulate matters (Cheng et al., 2017). The country and the people urgently need and expect pollution to be effectively governed and controlled. Therefore, in the process of green transformation under the guidance of the sustainable development concept in all walks of life, the research on O_3 driving factors in different cities and regions will provide crucial theoretical reference and basis. In recent years, scholars have adopted meteorological factors (He and He, 2018; Zhou et al., 2019), anthropogenic emissions(Lou et al., 2010; Pan et al., 2016), regional transmission effects (Chen et al., 2019; Liang et al., 2018), and O_3 generation sensitivity based on different scales of cities, regions, and countries (Wu et al., 2018; Fu et al., 2019) and so on, through the construction of atmospheric photochemical box model, or using correlation analysis, principal component analysis, trajectory cluster analysis, potential source contribution factor analysis and other methods, to analyze and study the driving factors of O_3 concentration, and continue to contribute to urban air pollution control.

At present, the research on the influencing factors of O_3 concentration has provided sufficient theoretical basis and test methods for subsequent exploration, but the areas targeted by these studies are mainly the relatively serious air pollution situation in a certain urban area, city or nationwide, such as Beijing-Tianjin-Hebei, Pearl River Delta, and Yangtze River Delta regions. It is relatively lacking in the comprehensive regional and national scale to consider the driving force of O_3 concentration. Moreover, there have been many studies using correlation analysis methods. Although it is possible to detect the influence direction of factors, it cannot accurately explain the influence of factors on the change of O_3 concentration, which is what geography detectors are good at. This paper selects the O_3 concentration monitoring day data of 364 cities in 2016, combines several relevant meteorological factors data and anthropogenic emissions data of these cities, and uses Geodetector to detect the spatial differentiation characteristics and driving factors of O_3 concentration changes in Chinese cities. This paper provides scientific and effective theoretical guidance and decision-making basis for the development of national O_3 pollution awareness and prevention measures.

2 Materials and methods

2.1 Data source

O_3 precursors produced by humans in production and discharged into the atmosphere are the main premise for most of the near-surface O_3 formation, and in this process, natural conditions play a crucial role, and because of its equally important influence on the accumulation and diffusion of O_3, meteorological factors and O_3 concentration changes have a strong correlation (Pan et al., 2016; Cheng et al., 2017). In this study, six of these meteorological factors, such as accumulated precipitation (PRE), surface pressure (PRS), 2-m relative humidity (RHU), sunshine duration (SSD), 2-m air temperature (TEM) and 10-m wind speed (WIN), which have important driving effects on O_3 concentration changes were selected, together with three O_3 precursors, CO (carbon monoxide), NOx (nitrogen oxides), VOC (volatile organic compounds), a total of nine evaluation factors to detect the driving factors of Chinese urban O_3 concentration.

The O_3 data is based on the maximum 8h (sliding) average concentration data obtained from the national urban air quality real-time release platform (http://106.37.208.233:20035/), and its time scale is from January 01, 2016 to December 31, 2016. A total of 367 national monitoring cities included in the 2016 O_3 concentration data (excluding Hong Kong, Macao and Taiwan and Sansha). Due to the serious lack of O_3 data in Zhuji City, Haimen City and Haidong District also lacked more data, while the data of other cities were relatively complete, therefore, the O_3 concentration data of 364 cities nationwide were selected for research.

The meteorological data includes meteorological daily data such as precipitation, air pressure, relative humidity, sunshine duration, temperature, and wind speed. The time scale is also the year from January 01, 2016 to December 31, 2016. These data were obtained from the China Meteorological Data Network (http://data.cma.cn/) ground data.

The anthropogenic emissions data comes from the MEIC model of Tsinghua University (http://www.meicmodel.org/). The gridd emissions inventory provided by the model website includes pollutant discharge data is stored in sectors such as agriculture, industry, residents, electricity, transportation, etc., stored in raster data. This study selects the 2016 emissions inventory, which includes annual data and monthly data on pollutant emissions such as CO, NOx, and VOC.

2.2 Data Preprocessing

The data used in the study included: O_3 concentration data, meteorological data, anthropogenic emissions data, and other ancillary data. After the preliminary preparation of the data, the minimum time scale of the O_3 precursor data is monthly, and the monitoring sites of the O_3 concentration data and meteorological data are mainly distributed in the urban area. For the unified calculation of the caliber, the CO, NOx, and VOC emission data are extracted to the city scale. According to the Ambient Air Quality Standard (GB 3095-2012), calculate the arithmetic mean of the maximum 8h (sliding) average concentration data on the O_3 day of each calendar month, and obtain the average concentration of O_3 month. The monthly average data of precipitation, air pressure, relative humidity, sunshine duration, temperature, and wind speed are also obtained by calculating the arithmetic mean of the respective daily value data in one calendar month. In addition, this paper divides the country into seven major geographical divisions, including East China, Central China, North China, South China, Northeast China, Northwest China and Southwest China [18], and organize the data by partition. Finally, the type of data, in the Geodetector, the dependent variable can be either a numerical quantity or a type quantity, but the independent variable only supports the type quantity, and each evaluation factor as an independent variable belongs to a numerical quantity. Therefore, the evaluation factors are discretized, and the values of each factor are divided into 10 levels using the quantile method (Wang and Xu, 2017; Huang et al., 2019).

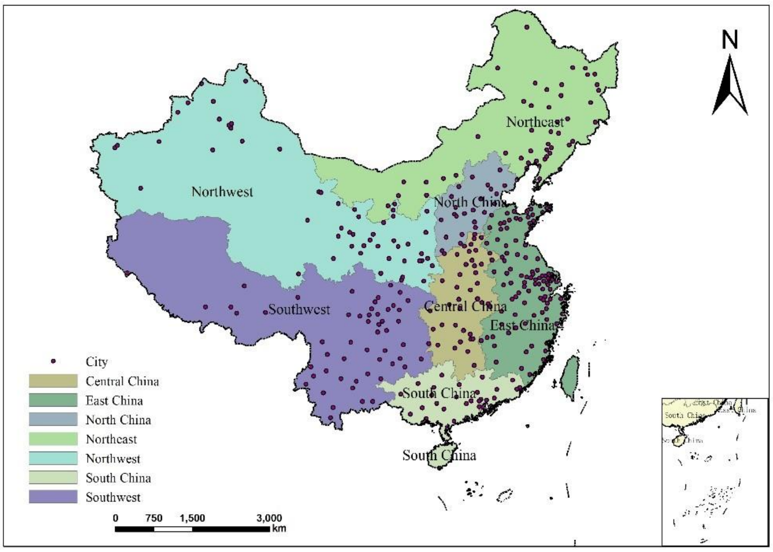

Fig. 1. Distribution map of China's air quality monitoring site

2.3 Geodetector model

The Geodetector is an analysis method developed by Wang Jinfeng (Wang and Xu, 2017) to detect spatial differentiation characteristics and its driving mechanism, and has been compiled into an easy-to-use software based on Excel (http://www.geodetector.org/). The principle is that the influence factors of the typed processing are set as independent variables, and the geographical phenomenon as the research object is regarded as the dependent variable, assuming that the two variables have significant consistency in spatial distribution, and whether the two are related to each other. In recent years, Geodetector have been widely used in food crop production (Ye et al., 2018), land development and utilization (Zhao et al., 2018), tourism development (Liang et al., 2018), ecological protection (Wang and Hu., 2018), etc.. It also has certain applications in environmental pollution (Zhou et al., 2019), providing a high-quality reference for the development of related research. Geography detectors include interaction detectors, ecological detectors, differentiation and factor detectors, and risk detectors. This paper mainly uses the functions of differentiation and factor detector and interaction detector to analyze the driving factors of urban O_3 concentration spatial distribution.

The differentiation and factor detector is mainly used to detect the explanatory power of each influence factor on the O_3 concentration. The expression is as follows:

$$P_{D,U} = 1 - \frac{1}{n\sigma_U^2}\sum_{i=1}^{m} n_{D,i}\,\sigma_{U_{D,i}}^2$$

In the formula: $P_{D,U}$is the driving force or explanatory force of the driving factor D to the change of O_3 concentration (equivalent to the q value used in the Geodetector software); $U$is the stratification of the driving factor D; n is the number of cities in the country that effectively monitor; σ_U^2为is the variance of the national effective monitoring of urban O_3 concentration; i is the sub-level stratification based on the difference of driving factors; m is the total number of secondary stratification; $n_{D,i}$ is the number of cities that effectively monitor the number of cities in the next level; $\sigma_{U_{D,i}}^2$ is the sub-level layer to effectively monitor the variance of urban O_3 concentration. When the value range of $P_{D,U}$ is [0, 1] and $P_{D,U}$ = 0, the driving force of the evaluation factor is 0, indicating that the O_3 concentration is spatially randomized. Evaluation factor has no correlation with O_3 generation. When $P_{D,U}$ = 1, it indicates that the change in O_3 concentration is completely dependent on the evaluation factor. Therefore, the larger the value of $P_{D,U}$, the stronger the explanatory power of the driving factor D to the change of O_3 concentration, that is, the greater the influence of O_3 generation (Wang and XU, 2010; Huang et al., 2019).

The interaction detector is used to detect the interpretative force of the O_3 concentration between the two evaluation factors in the interaction, that is, whether the driving force of the O_3 concentration is enhanced or weakened by the interaction of two factors. Or the impact of the two on the research object O_3 is independent and non-interference. The types of interaction between the two evaluation factors can be divided into five categories as shown in Table 1.

Table 1. The interactive categories of two factors and the interactive relationship

Description	Interaction
P(X1∩X2) < min(P(X1),P(X2))	Weaken; univariate
min(P(X1),P(X2)) < P(X1∩X2) < max(P(X1),P(X2))	Weaken; univariate
P(X1∩X2) > max(P(X1),P(X2))	Enhanced; bivariate
P(X1∩X2) = P(X1) + P(X2)	Independent
P(X1∩X2) > P(X1) + P(X2)	Nonlinearly enhance

3 Driving factors of O_3 concentration in Chinese cities

3.1 Analysis of Driving Factors of O_3 Concentration in Chinese Cities

According to the results of Geodetector differentiation and factor detection, the driving force of the nine evaluation factors passed the significance test on the time scale of 2016 (Table 2; Note:*, **, ***, indicates that the evaluation factors are significant at the levels of 0.1, 0.05, and 0.01, respectively) That is, meteorological factors and anthropogenic emissions factors have a significant impact on O_3 concentration changes. Among them, meteorological factors, especially temperature (0.335***) and sunshine duration (0.216***) have the greatest impact on O_3 concentration, and its explanatory power is far greater than the explanatory power of O_3 precursors. Among the other four meteorological factors, the driving force of precipitation (0.103***) and air pressure (0.123***) is also high. The relative humidity (0.035***) and wind speed (0.048***) are at the end of the meteorological factor. In contrast, anthropogenic emissions factors play a much less important role in the O_3 spatial difference generation process than these natural factors. However, it can also be found that, at the national scale, the explanatory power of VOC (0.009***) in the precursor is greater than the explanatory power of NOx (0.005***). This result is consistent with existing research on the sensitivity of urban O_3 generation[8] . In addition, the influence of CO (0.015***) is greater than that of NOx and VOC, and it can be judged that O_3 generation in this large area of the country is CO-controlled. This is different from the view that NOx and VOC are generally considered to be the most important precursors of O_3 formation. In general, although the precursor is indispensable for the formation of O_3, its influence on the change of O_3 concentration is almost negligible compared with the influence of meteorological factors. Therefore, it can be broadly stated that meteorological factors dominate the influence of the spatial pattern of O_3 concentration. Specifically, temperature and duration of sunshine are the main driving factors of O_3 pollution in Chinese cities, with temperature being the most critical.

Table 2. The annual and seasonal p values of driving factors for O_3 concentrations at the national scale.

Time	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Year	0.103***	0.123***	0.035***	0.216***	0.335***	0.048***	0.015***	0.005***	0.009***
Spring	0.089***	0.050***	0.140***	0.181***	0.123***	0.103***	0.010	0.013	0.013

Summer	0.087***	0.080***	0.159***	0.102***	0.102***	0.098***	0.020**	0.027***	0.026***
Autumn	0.091***	0.129***	0.107***	0.204***	0.439***	0.030***	0.012	0.007	0.011
Winter	0.063***	0.049***	0.086***	0.139***	0.110***	0.026***	0.013	0.008	0.007

After the interaction detector calculation, the interaction driving force between the evaluation factors of 2016 and the national urban O_3 concentration was obtained (Fig. 2). The interaction between relative humidity and temperature (0.581), and the interaction between sunshine duration and temperature (0.570) all reached 0.5 or higher, which is the highest among all factors. This is mainly because in the process of photochemical reaction of the troposphere to generate O_3, the light, temperature and moisture in the air are closely related to the reaction [17], and the water vapor also has a dilution effect on O_3. In addition, the two factors of temperature and sunshine duration are the largest in explaining the change of O_3 concentration, and the relative humidity is less explanatory, but the synergistic effect of relative humidity and temperature is the strongest. Therefore, the interaction between relative humidity and temperature is far stronger than the interaction between temperature and sunshine duration. In terms of the type of interaction, in addition to the synergy between precipitation and temperature, the synergy between air pressure and temperature, the synergistic effect of sunshine duration and wind speed are two-factor enhancement， the interaction between all other factors is nonlinear enhancement. Among them, the interaction between precipitation and relative humidity, the interaction between CO and VOC, the interaction between CO and NOx, and the interaction between NOx and VOC are the most significant nonlinear enhancements. The P value of the interaction between them is much larger than the result of adding the two P values. The interaction between CO and NOx is even close to 4 times the sum of their driving forces, and the interaction effect is extremely amazing. Although their synergistic driving force is not very high, but one of the factors change will have a greater impact on the O_3 concentration. Therefore, at the national scale, the interaction between CO and NOx on the spatial layout of Chinese urban O_3 is the most obvious, and the interaction between relative humidity and temperature is the most influential. The changes in these two sets of factors can be reflected to the O_3 concentration fastest and most violently.

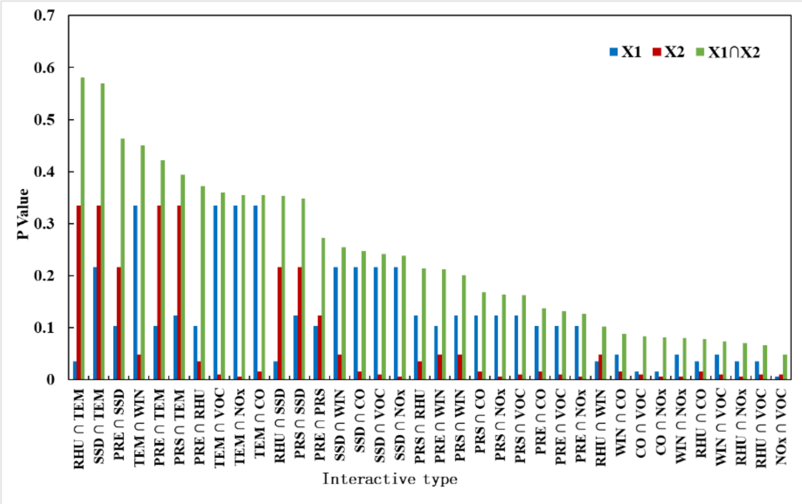

Fig. 2. The annual interactive *p* value and the original *p* value of each pair of factors.

3.2 Seasonal Difference Analysis of Driving Factors of O_3 Concentration in Chinese Cities

According to Table 2, although the influence of natural conditions and human conditions, the driving force of the artificially emitted O_3 precursors in the four seasons is all lower than that of the six meteorological factors. Still the influence of natural conditions is stronger. However, according to each evaluation factor, the driving force of each factor is very different between the whole year and the seasonal scale, and there are great differences in different seasons. As a result, the dominant factors of the spatial layout of Chinese cities in different seasons are different.

In terms of natural factors, the dominant factor in spring is the duration of sunshine (0.181***), while the relative humidity (0.140***) is second, and the wind speed (0.103***) is the strongest in the four seasons. The dominant factor in summer is relative humidity (0.159***), while the explanatory power of sunshine duration (0.102***) and temperature (0.102***) is at the end of the four seasons， indicating that the increase in the duration of sunshine and the rise in temperature are inversely proportional to their respective explanatory powers. The dominant factor in the fall is the temperature (0.439***), which is the highest in the four seasons with the influence of sunshine duration (0.204***), precipitation (0.091***), and air pressure (0.129***). The dominant factors in winter are sunshine duration (0.139***) and temperature (0.110***), their P value is greater than summer, and the remaining P values of the meteorological factors are the lowest in the four seasons.

The explanatory power of CO, NOx and VOC in spring, autumn and winter failed to pass the significance test, indicating that they have certain influence on the change of O_3 concentration in these three seasons, but from the national point of view, this effect is not obvious. In the summer, the explanatory power of CO (0.020**), NOx (0.027***), and VOC (0.026***) reached the highest level in the year, Especially NOx, which is more than 5 times the annual average. This may be related to higher temperatures and stronger, longer-lasting illumination in summer, indicating that to some extent meteorological factors influence the driving force of O_3 precursors on O_3 concentration distribution, and this effect is positive.

From the interaction between the two factors, due to the high P value of temperature (0.439***) and sunshine duration (0.204***) in autumn, the highest interactive driving force in autumn is much larger than the other three seasons. The interaction driving force and distribution trend between spring and summer are more consistent. In winter, the P value of the impact factor is generally low, resulting in the overall level of interaction driving force at the lowest position in the four seasons. Among them, the synergistic effect of sunshine duration and temperature has the highest explanatory power in spring, autumn and winter. The highest in summer is the interaction between air pressure and relative humidity, and the synergistic effect of relative humidity and temperature is second in all four seasons, which is consistent with the results of detection at the annual scale.

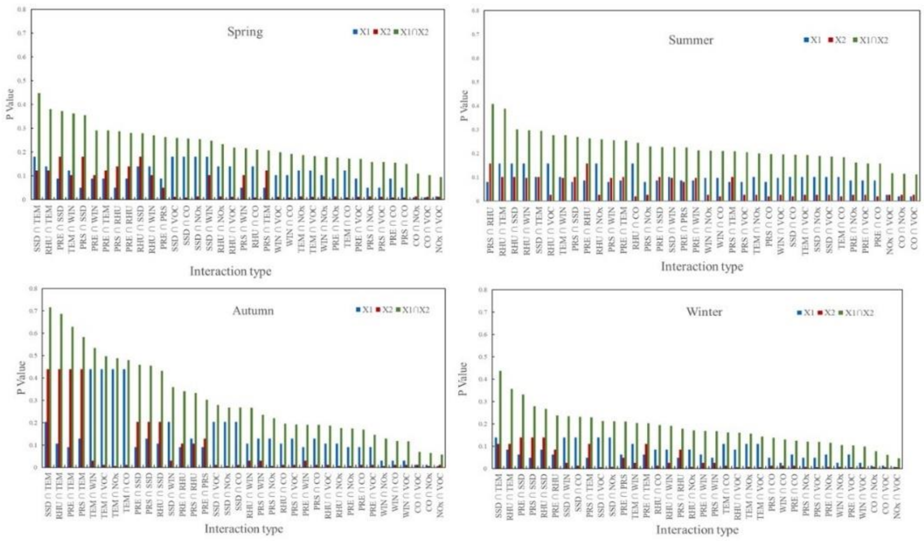

Fig. 3. Interactive driving force of O_3 concentration on national scale in different seasons

3.3 Regional Difference Analysis of Urban O_3 Concentration Driving Factors

According to China's seven geographical divisions, the paper divides the country into seven regions: Central China, East China, North China, Northeast China, Northwest China, South China and Southwest China. Based on this, the performance of the evaluation factors in different regions is detected (Table 3, Figure 4).), to analyze the driving factors of spatial differences in urban O_3 in various regions.

Table 3. Annual *p* values of driving factors in 7 regions of China.

Area	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Central China	0.104***	0.216***	0.145***	0.542***	0.585***	0.055*	0.023	0.024	0.068***
East China	0.064***	0.346***	0.055***	0.325***	0.391***	0.035***	0.034***	0.009	0.030***
North China	0.441***	0.296***	0.033	0.342***	0.615***	0.054*	0.081**	0.130***	0.028
Northeast	0.364***	0.060**	0.093**	0.366***	0.472***	0.095***	0.084***	0.027	0.060***
Northwest	0.293***	0.041	0.090***	0.295***	0.485***	0.126***	0.039**	0.022	0.031*
South China	0.084	0.061	0.044	0.357***	0.210***	0.065	0.055	0.024	0.033
Southwest	0.070***	0.076***	0.114***	0.158***	0.183***	0.120***	0.014	0.051**	0.027

(1) Among the evaluation factors in Central China, precipitation (0.104***), air pressure (0.216***), relative humidity (0.145***), sunshine duration (0.542***), temperature (0.585***) , wind speed (0.055*) and VOC (0.068***) all passed the significance test. Among them, the driving force of sunshine duration and temperature is far greater than the driving force of other factors, indicating that sunshine duration and temperature are the dominant factors of O_3 spatial difference in Central China. In the O_3 precursor, VOC has the highest driving force, and CO and NOx fail to pass the significance test. In addition, the interaction detection results in the region showed that the interaction between relative humidity and temperature (0.829), and the interaction between sunshine duration and temperature (0.822) reached P value 0.8 or more, which had the strongest impact on Central China. Therefore, for O_3 pollution in Central China, based on the relative humidity, sunshine and temperature conditions for a period of time, reasonable control of VOC emissions will achieve relatively obvious effects in a short period of time.

(2) The evaluation factors in East China passed the significant test except for NOx. The air pressure (0.346***), the duration of sunshine (0.325***), and the temperature (0.391***) were the dominant factors in the region. The precipitation in East China (0.064***), South China (0.084), and Southwest (0.070***) has less impact on O_3 concentration changes than in other areas due to the high precipitation. In terms of anthropogenic pollution emissions, CO (0.034***) and VOC (0.030***) have a certain driving force for the formation of O_3. From the perspective of interaction, the top three influences in East China are the interaction between sunshine duration and temperature (0.711), the interaction between relative humidity and temperature (0.680), and the interaction between precipitation and sunshine duration (0.649). It can be found that although the explanatory power of precipitation is small, it can have a greater impact on the O_3 concentration after combining other factors. The pollution control in East China mainly considers the control of CO and VOC emissions under the influence of these three types of interaction.

(3) Relative humidity and VOC in North China failed to pass the significance test, but the explanatory factors of other factors were generally stronger. Precipitation (0.441***) and temperature (0.615***) are the dominant factors in the region, and their explanatory power is the highest among the 7 major divisions. The explanatory power of CO (0.081**) and NOx (0.130***) has reached an astonishing height. This is mainly due to the industrial development of the Beijing-Tianjin-Hebei region, and large-scale

heavy pollution industries in Shanxi and central Inner Mongolia. The pollution situation is severe. The O_3 precursors have large emissions, and the local precipitation is less. The erosion ability of O_3 is weaker and the temperature is lower. The changes of these factors will be strongly and quickly feedback to the change of O_3 concentration. In addition, the interaction between the duration of sunshine and temperature (0.825), the interaction of temperature and wind speed (0.801) also has a crucial impact. The main focus of North China should be on industrial regulation, environmental protection, and economic development coordination, and pay special attention to CO and NOx emissions.

(4) The northeastern region includes the three northeastern provinces, which are the old industrial strong provinces and the eastern Inner Mongolia region. CO (0.084***) and VOC (0.060***), which passed the significant test in their precursors, have strong driving force. The main driving factors in the region are precipitation (0.364***), sunshine duration (0.366***) and temperature (0.472***), which are basically consistent with North China, and the two regions have certain similarities. The strongest interaction in the Northeast is the interaction of relative humidity and temperature (0.720) and the interaction of relative humidity and precipitation (0.713). For the northeast region, the overall temperature is lower, the duration of sunshine is shorter, and the photochemical reaction is weaker. In the case of accumulation of precursors, a short temperature rise and a longer sunshine time will generate a large amount of O_3 pollution. The flushing of the atmosphere by precipitation and relative humidity is particularly important.

(5) The dominant factors in the northwestern region are precipitation (0.293***), duration of sunshine (0.295***), and temperature (0.485***). Air pressure and NOx did not pass the significance test, while the explanatory power of wind speed (0.126***) is the strongest in several regions. This is because the northwestern region is vast, the population and industrial distribution are far less dense than other regions, and atmospheric transport has a greater impact on O_3 concentration. The interaction between sunshine duration and temperature (0.626), the interaction between precipitation and sunshine duration (0.614) have the strongest interaction influence. Pollution control in the northwestern region needs to combine regional characteristics, consider precipitation, temperature, sunshine and wind speed, and delineate key areas to control CO and VOC emissions.

(6) In South China, only the sunshine duration (0.357***) and the temperature (0.210***) passed the significant test. Other factors have certain influence in the region, but the impact is not obvious enough. The type with the highest interaction driving force is the interaction between sunshine duration and wind speed (0.531) and the interaction between precipitation and sunshine duration (0.506). The visible part is located in the tropical South China region. Multiple typhoons, high temperatures, heavy rainfall and long sunshine provide extremely complex and powerful natural driving in the region, especially in the highly industrialized, urbanized and O_3 polluted areas of the Pearl River Delta.

(7) The sunshine duration (0.158***), temperature (0.183***), relative humidity (0.114***) and wind speed (0.120***) in the southwestern region have a greater impact on O_3 concentration. In terms of pollutant emissions, only NOx (0.051**) passed the

significance test, but its explanatory power was only lower than North China in the 7 geographical divisions. In terms of interaction, the interaction between relative humidity and temperature in the region (0.444) is the strongest, but it is the weakest in the 7 regions. On the whole, the impact of O_3 concentration in the southwest on the national scale is also the smallest. The Sichuan Basin and the Yunnan-Guizhou Plateau in the southwest have many clouds, the water system is developed, and the atmosphere is in a state of high humidity all the year round. At the same time, the wind speed in some areas has a significant impact on the accumulation of precursors. These factors and the sunshine and temperature which affect photochemical reactions are the dominant factors in the spatial distribution of O_3 in Southwest China.

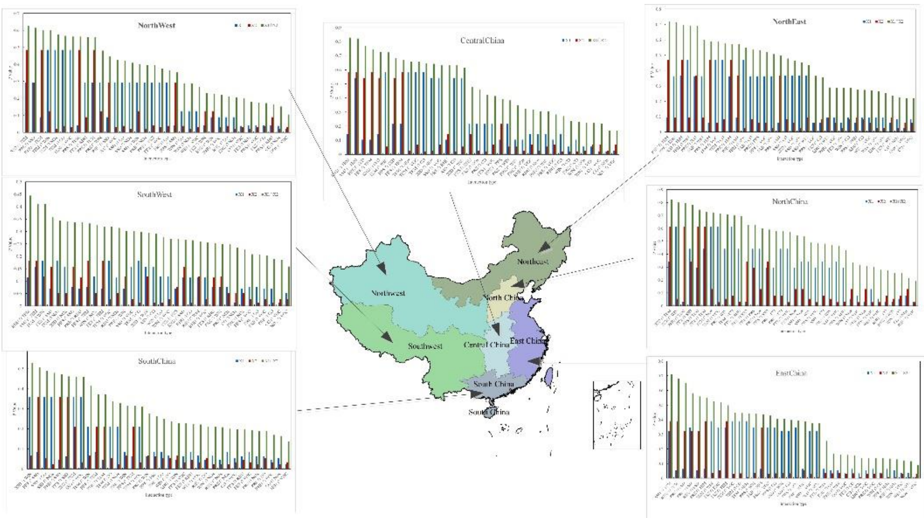

Fig. 4. Annual interaction *p* values between influencing factors over the 7 regions in China.

3.4 Seasonal Difference Analysis of Driving Factors of O_3 Concentration in Different Areas

Based on the overall analysis of the seven geographical divisions of Central China, East China, North China, Northeast China, Northwest China, South China and Southwest China, the time scale is further subdivided to detect the driving factors and differences of each region in different seasons in spring, summer, autumn and winter. The interactive detection results are shown in Fig.5, Fig.6, Fig.7, and Fig.8.

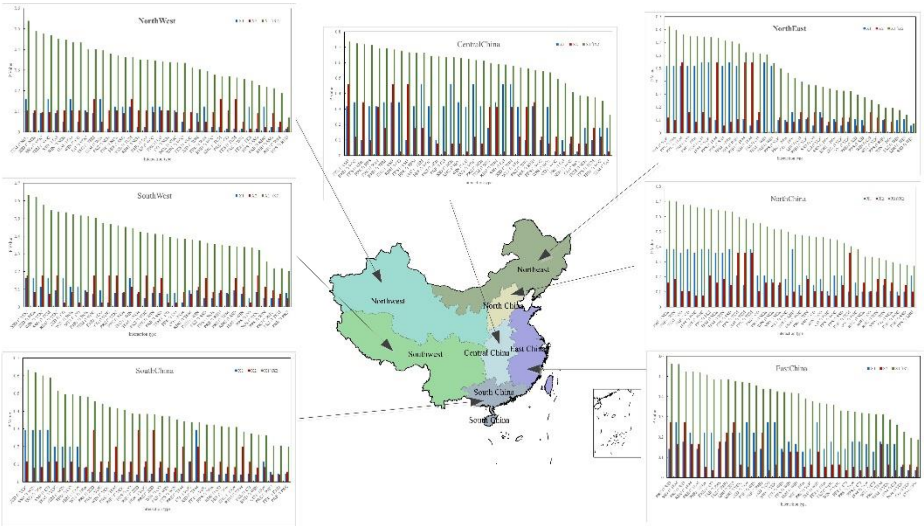

Fig. 5. The interaction p values between influencing factors in spring over the 7 regions in China.

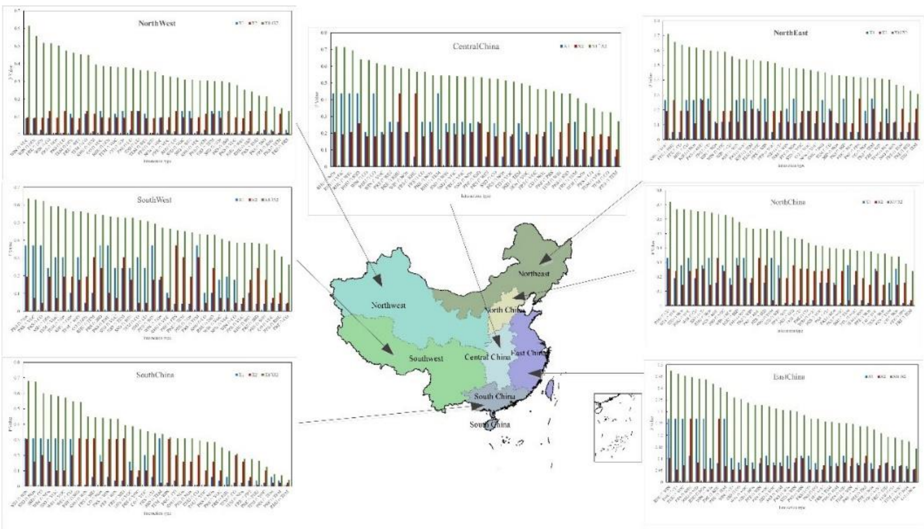

Fig. 6. The interaction p values between influencing factors in summer over the 7 regions in China.

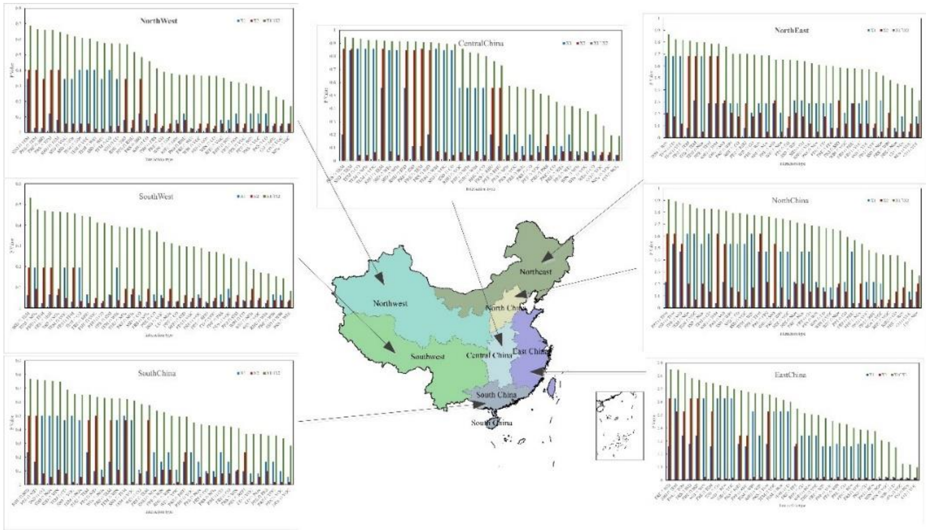

Fig. 7. The interaction *p* values between influencing factors in autumn summer over the 7 regions in China.

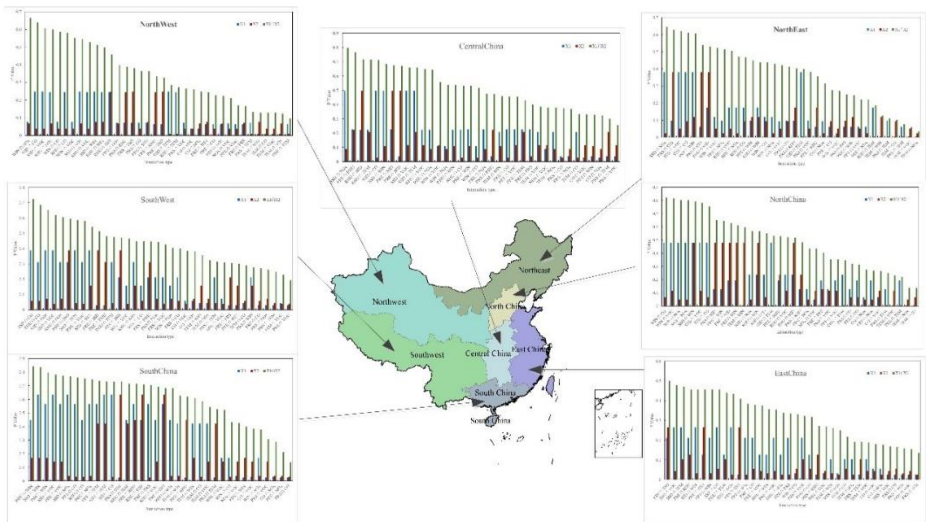

Fig. 8. The interaction *p* values between influencing factors in winter over the 7 regions in China.

(1) O_3 precursors discharged from Central China (Table 4) did not pass significant tests in all four seasons, and meteorological conditions remained the main driving factor in the region in different seasons. The dominant factor in spring is precipitation, relative humidity and sunshine duration. The strongest interaction type is the interaction between precipitation and sunshine duration. Wind speed is the only factor that passes the test in summer, which dominates the O_3 drive of the season. The combination of relative

humidity and NOx has the strongest interaction. In the autumn, precipitation, air pressure, relative humidity, sunshine duration and temperature passed the significance test. The latter two had the greatest impact on O_3 pollution in Central China, and the synergistic interpretation of pressure and temperature was close to 1, and the interaction was extremely obvious. The dominant factor in winter is the duration of sunshine. Among the remaining factors, precipitation, relative humidity and temperature have also passed the significance test. The strongest type of interaction in this season is sunshine duration and NOx. It can be seen that although the influence of NOx itself on the Central China region is not obvious enough, it can greatly drive the change of O_3 concentration in the region under the synergy of other factors.

Table 4. seasonal *p* values of driving factors in Central China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.317^{**}	0.097	0.345^{***}	0.460^{***}	0.178	0.314	0.026	0.079	0.123
Summer	0.267	0.061	0.438	0.260	0.101	0.206^{*}	0.182	0.205	0.193
Autumn	0.111^{*}	0.203^{***}	0.559^{***}	0.846^{***}	0.857^{***}	0.072	0.042	0.043	0.063
Winter	0.225^{***}	0.039	0.223^{***}	0.498^{***}	0.208^{***}	0.110	0.028	0.087	0.116

(2) In East China (Table 5), all factors except CO and NOx passed the significant test in spring, in which the relative humidity and sunshine duration have the highest driving force. The factors that pass the test in summer are relative humidity, wind speed and VOC. In spring and summer, we can start from controlling the emission of VOC and get better pollution control effect in a short period of time. Precipitation, air pressure, relative humidity, duration of sunshine, and temperature passed the significant test in the fall, with the latter two being the dominant factor. In winter, only the precipitation, relative humidity and duration of sunshine have passed the test, in which the duration of sunshine is the main drive. The interaction between precipitation and sunshine duration dominates in spring, autumn and winter, and the interaction between relative humidity and wind speed is the strongest in summer.

Table 5. seasonal p values of driving factors in East China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.142^{***}	0.176^{**}	0.221^{***}	0.274^{***}	0.166^{***}	0.128^{***}	0.038	0.052	0.064^{**}
Summer	0.081	0.111	0.271^{***}	0.084	0.070	0.102^{**}	0.054	0.057	0.071^{**}
Autumn	0.260^{***}	0.279^{***}	0.342^{***}	0.626^{***}	0.529^{***}	0.025	0.019	0.012	0.021
Winter	0.212^{***}	0.024	0.127^{*}	0.265^{***}	0.104	0.031	0.056	0.026	0.043

(3) The performance of most evaluation factors in different seasons in North China (Table 6) is not obvious enough, but the explanatory power of the factors that passed

the significance test has reached a high level. The dominant factors in spring are precipitation and temperature. The dominant type of interaction is precipitation and NOx. The scouring effect of precipitation on NOx is obvious. The dominant factor in summer is relative humidity. The dominant interaction type is the interaction between sunshine duration and temperature. The dominant factors in autumn are precipitation, sunshine duration and temperature. The dominant interaction type is the interaction between air pressure and temperature. The dominant factors in winter are relative humidity, sunshine duration and wind speed. The driving intensity of wind speed is the highest in the four seasons, indicating that the accumulation of O_3 and its precursors in winter is serious in North China, and the trans-regional transport of the atmosphere is particularly important. In addition, the combination of wind speed and CO is the dominant type of interaction for the season.

Table 6. seasonal *p* values of driving factors in North China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.381*	0.211	0.102	0.147	0.359***	0.187	0.105	0.161	0.074
Summer	0.018	0.159	0.330**	0.282	0.037	0.191	0.257	0.143	0.240
Autumn	0.472***	0.218	0.039	0.536***	0.620***	0.169	0.137	0.204	0.071
Winter	0.193	0.126	0.235***	0.478***	0.007	0.480***	0.065	0.049	0.116

(4) Northeast region (Table 7) precipitation has the strongest influence in spring, and the temperature has the highest explanatory power in autumn, and the winter sunshine duration can produce the strongest drive. The relative humidity influences in summer and autumn are similar, with slightly higher in autumn. However, only the P value of summer CO emissions in the O_3 precursor passed the significance test, which makes the northeast region no longer completely dominated by meteorological conditions in summer, but is dominated by relative humidity, temperature and CO. From the aspect of the interaction of evaluation factors, the strongest driving types from spring to winter are precipitation and VOC interaction, relative humidity and VOC interaction, temperature and wind speed interaction, and sunshine duration and NOx interaction. It can be seen that the old industrial strong provinces have strong precurors.

Table 7. seasonal *p* values of driving factors in Northeast China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.519***	0.101	0.108	0.056	0.548***	0.005	0.160	0.084	0.117
Summer	0.051	0.275	0.266*	0.114	0.207***	0.120	0.194**	0.110	0.193
Autumn	0.287	0.080	0.287*	0.311***	0.683***	0.210	0.176	0.050	0.118
Winter	0.062	0.096	0.175	0.381***	0.004	0.120	0.096	0.024	0.052

(5) In the northwestern region (Table 8), there are very few evaluation factors passed the significance test. In the spring and summer, there is no evaluation factor that passed the significance test. In autumn, only precipitation, sunshine duration and temperature passed the test. In winter, the relative humidity and the duration of sunshine passed the significance test. This may be because the northwest is inland, far from the coast, the economy is relatively backward, and the meteorological environment is complex and changeable. The distribution of O_3 concentration in different cities and even areas is quite different, and the driving factors are different, which fails to form a unified impact on the whole. This situation is particularly evident in spring and summer. In addition, the combinations of factor interactions that have the greatest impact from spring to winter are temperature and NOx, followed by wind speed and VOC, sunshine duration and temperature, wind speed and NOx.

Table 8. seasonal p values of driving factors in Northwest China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.123	0.016	0.023	0.091	0.162	0.051	0.104	0.104	0.096
Summer	0.027	0.009	0.016	0.133	0.118	0.091	0.131	0.094	0.098
Autumn	0.030	0.121**	0.080	0.345***	0.401***	0.025	0.044	0.059	0.056
Winter	0.062	0.072	0.243***	0.246***	0.008	0.077	0.039	0.067	0.036

(6) In south China (Table 9), there is no evaluation factor passed the test in spring, and the interaction between the duration of sunshine and VOC has the greatest impact on the season. The dominant factors in summer are the duration of sunshine and wind speed. The dominant interaction is also the interaction of these two factors. The P value of wind speed is the highest in the four seasons, which is consistent with the impact of summer typhoon on the transport of O_3 pollution area in this area. The dominant factors in autumn are the duration of sunshine and temperature. The dominant interaction is the interaction between relative humidity and sunshine duration. The dominant factors in winter are precipitation, relative humidity, duration of sunshine and temperature. The dominant interaction is the interaction between relative humidity and wind speed. The emission of O_3 precursors in this area has not been significantly affected in the four seasons. The reason may be that the urbanization and industrialization levels of the Pearl River Delta region and Guangxi and Hainan are quite different, and the driving factors for O_3 concentration are different. On the whole, it failed to form a strong leading role.

Table 9. seasonal p values of driving factors in South China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.045	0.054	0.041	0.293	0.200	0.079	0.113	0.083	0.116

Summer	0.038	0.061	0.010	0.309***	0.021	0.305***	0.201	0.160	0.102
Autumn	0.167	0.100	0.235	0.501***	0.469***	0.108	0.081	0.057	0.020
Winter	0.568***	0.025	0.446***	0.634***	0.423***	0.170	0.031	0.037	0.144

(7) Precipitation, wind speed, CO and VOC in the Southwest (Table 10) have no significant effect on the overall O_3 concentration change in the region. The dominant factor in spring is the duration of sunshine, the dominant interaction is the duration of sunshine and VOC; the summer is dominated by air pressure, duration of sunshine, temperature, and NOx, among which the interaction between pressure and NOx is the strongest. In autumn, there is no factor passed the test; the winter dominant factors are air pressure, relative humidity and sunshine duration, and the interaction between sunshine duration and CO is the strongest, and the relative humidity driving force of this season is the highst in the four seasons.

Table 10. seasonal p values of driving factors in Southwest China

Season	PRE	PRS	RHU	SSD	TEM	WIN	CO	NOx	VOC
Spring	0.081	0.051	0.096	0.164*	0.073	0.115	0.023	0.084	0.176
Summer	0.041	0.372***	0.104	0.245***	0.305***	0.176	0.048	0.195*	0.074
Autumn	0.064	0.029	0.024	0.063	0.195	0.038	0.034	0.091	0.048
Winter	0.029	0.212***	0.312***	0.388***	0.045	0.158	0.058	0.071	0.040

4 Conclusion

In general, meteorological factors dominate the change of O_3 concentration in Chinese cities, but there are some differences in the driving forces of different evaluation factors at different scales, different regions and different seasons. Therefore, in some cases, the driving force of the O_3 precursor is no less than that of some meteorological factors.

From the national scale, the driving factors of sunshine duration and temperature are the most significant. Among them, temperature is the most critical, while the relative humidity and temperature groups have prominent interactions.

By analyzing the national pollution from a seasonal perspective, it can be found that the dominant factors of O_3 pollution in spring and winter are the duration of sunshine, the relative humidity in summer and the temperature in autumn. In addition, the main interactions in spring, autumn and winter are sunshine duration and temperature. In summer, it is air pressure and relative humidity.

From the perspective of the seven geographical divisions, the temperature dominates the variation and distribution of O_3 concentrations in the six regions of Central China, East China, North China, Northeast China, Northwest China and Southwest China. The O_3 pollution in South China is dominated by the duration of sunshine. In terms of factor interaction, the strongest interactions in Central, Northeast, and Southwest regions are combined with relative humidity and temperature. The interaction between sunshine duration and temperature dominates in East China, North China, and Northwest China, while South China has the strongest interaction between sunshine duration and wind speed. It can be found that there are large differences between South China and the other six regions.

From the seasonal influences of different sub-areas, the influencing factors of O_3 concentration changes in each region in different seasons are very different. The influence of evaluation factors on this scale is generally not obvious, and the driving factors and interactions are complicated. The dominant factor for spring and winter in Central China is the duration of sunshine. The driving of wind speed is the main influence in summer. The dominant factor in autumn is temperature, and the winter is the length of sunshine. The strongest types of interactions from spring to winter are precipitation and sunshine duration, relative humidity and NOx, air pressure and temperature, and sunshine duration and NOx. The dominant factor in the spring, autumn and winter of East China is the duration of sunshine. The dominant interaction is the interaction between precipitation and sunshine duration. The dominant factor in summer is relative humidity. The dominant interaction combination is relative humidity and wind speed. The dominant factors from spring to winter in North China are precipitation, relative humidity, temperature and wind speed, while the dominant interactions are combined with precipitation and NOx, relative humidity and CO, pressure and temperature, wind speed and CO. The dominant factors in spring and autumn in Northeast China are temperature, summer is dominated by relative humidity, and winter is sunshine duration. The dominant interactions of the four seasons are precipitation and VOC, relative humidity and VOC, temperature and wind speed, sunshine duration and NOx. In the northwestern region, all the factors in the spring and summer failed to pass the significance test, so it is impossible to judge the dominant factors of the two seasons, and the factors that mainly affect autumn and winter are the temperature and the duration of sunshine. Temperature and NOx, wind speed and VOC, sunshine duration and temperature, wind speed and NOx are the main interactions of the four seasons. The spring evaluation factors in South China have not passed the test. The dominant factors in summer, autumn and winter are the sunshine duration. The dominant interactions of the four seasons are sunshine duration and VOC, sunshine duration and wind speed, relative humidity and sunshine duration, relative humidity and wind speed. The evaluation factor of Southwest China did not pass the significant test in autumn, the factors that dominate spring and winter are the duration of sunshine, and the summer is the pressure. The dominant combinations of interactions in the four seasons are sunshine duration and VOC, pressure and NOx, sunshine duration and temperature, sunshine duration and CO.

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References:

1. Fishman J, Crutzen P J. The origin of ozone in the troposphere [J]. Nature, 1978, 274 (5674):855-858.
2. Lou Sijia, Zhu Bin, Liao Hong. Impacts of O_3 precursoronsurfaceO_3 concentration over China[J]. Trans Atmos Sci, 2010, 33(4):451-459.
3. Dong Shaoni, Li Bo. Sources and characteristics of ozone pollution and the significance of ozone monitoring [J]. Environment & Development, 2019, 31(02):189+191.
4. Pan Benfeng, Cheng Linjun, Wang Jianguo, et al. Characteristics and Source Attribution of Ozone Pollution in Beijing-Tianjin-Hebei Region [J]. Environmental Monitoring in China, 2016, 32(05):17-23.
5. Cheng Linjun, Wang Shuai, Gong Zhengyu, et al. Spatial and seasonal variation and regionalization of ozone concentrations in China [J]. China Environmental Science, 2017, 37(11):4003-4012.
6. He Wei, He Tao. Relationship Between Atinospheric Ozone Concentration and Meteorological Conditions in Wujing District [J]. Anhui Agricultural Science Bulletin, 2018, 24(24):91-93.
7. Chen Chao, Yan Renchang, Ye hui, et al. Researth on the characteristics of ozone pollution in Hangzhou[J]. Environmental pollution & Control, 2019, 41(03):339-342.
8. Wu kai, Kang Ping, Yu Lei, et al. Pollution status and spatio-temporal variations of ozone in China during 2015—2016 [J]. Acta Science Circumstantiae, 2018, 38(06):2179-2190.
9. Zhou Xuesi，Liao Zhiheng，Wang Meng，et al．2019．Characteristics of ozone concentration and its relationship with meteorological factors in Zhuhai during 2013—2016 [J]．Acta Scientiae Circumstantiae，39(1) : 143-153.
10. Wang Jinfeng, Xu Chengdong. Geodetector: Principle and prospective [J]. Acta Geograhica Sinica, 2017, 72(01):116-134.
11. Ye Yanjun, Qi Qingwen, Jiang Lili, et al. Impact factors of grain output from farms in Heilongjiang reclamation area based on geographical detector [J]. Geographical Research, 2018, 37(01):171-182.
12. Zhao Xiaofeng, Li Yaya, Zhao Yuntai, et al. Spatiotemporal Differences and Driving Factors of Land Development Degree in China Based on Geographical Detector [J]. Resources and Environment in the Yangtze Basin. 2018, 27(11):2425-2433.
13. Liang Qiaoxia, Huang Jie, Xie Xia, et al. Study on tourism spatial differentiation characteristics and influencing factors in northern slope of Tianshan Mountains based on geodetector[J]. Journal of Nortwest Normal University (Natural Science), 2018, 54(06):82-88.
14. Wang Yu, Hu Baoqing. Spatial and temporal differentiation of ecological vulnerability of Xijiang river in Guangxi and its driving mechanism based on GIS [J]. Journal of Geo-information Science, 2018, 20(7):947-956.
15. Zhou Liang, Zhou Chenghu, Yang Fan, et al. Spatio-temporal evolution and the influencing factors of PM2.5 in China between 2000 and 2015 [J]. Journal of Geographical Sciences, 2019, 29(02):253-270.

16. Huang Xiaogang, Zhao Jingbo, Cao Junji, et al. Spatial-temporal Variation of Ozone Concentration and its Driving Factors in China [J]. Environmental Science, 2019, 40(03):1120-1131.
17. Li Yang. A study on the Temporal and Spatial Variations of Tropospheirc Ozone and its Impacting Factors [D]. Lanzhou University, 2018.
18. Li Xiaoyang, Li Sijie, Liu Pengfei, et al. Spatial and temporal variations of ozone concentrations in China in 2016 [J]. Acta Scientiae Circumstantiae, 2018, 38(04):1263-1274.
19. FU Zhiqiang, DAI Chunhao, WANG Zhangwei, et al. Sensitivity analysis of atmospheric ozone formation to its precursors in summer of Changsha [J]. Environmental Chemistry, 2019, 38(3):531-538.
20. Liang Yu, Liu Yuhan, Wang Hongli, et al. 2018. Regional characteristics of ground-level ozone in Shanghai based on PCA analysis [J]. Acta Scientiae Circumstantiae, 38(10):3807-3815