Journal of Global Change Data & Discovery. 2022, 6(3): 448-458
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Analysis of Ozone Pollution Characteristics and Impact Factors in Haikou City (2016–2020)

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Abstract: To study the characteristics of ozone pollution changes in tropical island cities and their relationship with meteorological factors, daily and hourly air quality automatic monitoring data and meteorological observations in Haikou city from 2016 to 2020 were selected for analysis. The results show that the peak ozone concentration period of Haikou city is significantly different from that of inland cities, mainly in the autumn and winter seasons (from October to December). Regional climate differences are the main reason for the time distribution. The diurnal variation presents an obvious single-peak feature, with a nadir at 8:00 and a peak at 14:00–16:00. In recent years, the range of ozone pollution in urban areas has gradually expanded, and its degree has worsen; ozone concentration is positively correlated with CO concentration and wind speed, and negatively correlated with humidity. The main meteorological factors that affect the change of ozone concentration in Haikou city in autumn and winter are not air pressure and temperature.

Keywords: Haikou city; variation characteristic; precursor; correlation analysis; meteorological factor

DOI: https://doi.org/10.3974/geodp.2022.03.16

CSTR: https://cstr.escience.org.cn/CSTR:20146.14.2022.03.16

Dataset Availability Statement:

The dataset supporting this paper was published and is accessible through the *Digital Journal of Global Change Data Repository* at:https://doi.org/10.3974/geodb.2022.05.04.V1 or https://cstr.escience.org.cn/CSTR:20146.11.2022.05.04.V1.

1 Introduction

In recent years, O_3 has become one of the most critical pollutants affecting urban air quality in China, and O_3 pollution in cities and regions is on the rise[1]. According to the 2019 China Ecological Environment Bulletin, in 337 cities at prefectural level and above in China, the average annual concentrations of $PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2 and CO were 36 μg/m^3, 63 μg/m^3, 148 μg/m^3, 11 μg/m^3, 27 μg/m^3 and 1.4 mg/m^3, respectively. Compared with 2018, O_3 concentration has increased, and the proportion of days exceeding the standard is also on

Received: 10-06-2022; **Accepted:** 11-08-2022; **Published:** 25-09-2022

Foundation: Haikou Ecological and Environmental Bureau (HXSJ-CG-2021102)

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Data Citation: [1] Cai, J. Z., Wang, S. H., Hu, J. X. Analysis of ozone pollution characteristics and impact factors in Haikou city (2016–2020) [J]. *Journal of Global Change Data & Discovery*, 2022, 6(3): 448–458. https://doi.org/10. 3974/geodp.2022.03.16. https://cstr.escience.org.cn/CSTR:20146.14.2022.03.16.

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the rise. O_3 pollution has become increasingly prominent[2]. At present, with the rapid economic development and the continuous expansion of the urban scale, O_3 pollution has become an important environmental problem that urgently needs to be solved in the process of urban development in China and is one of the hot research topics in the field of atmospheric chemistry and environmental science. It is generally believed that the changing trend of O_3 pollution is subject to the joint action of the emission of precursor substances, meteorological conditions, and chemical reactions and that there is a significant correlation between the change of O_3 concentration and meteorological conditions, with obvious seasonal variation characteristics[3,4]. However, domestic analysis and research on O_3 pollution are mainly concentrated in some key cities and economically developed areas. In recent years, the economic development and urban expansion of Hainan province have led to a worsening air quality of Hainan Island, and the situation of O_3 pollution has become increasingly severe[5,6]. Haikou is a tropical island city with unique natural conditions, its O_3 pollution characteristics and meteorological impact have certain typicality. Therefore, based on the concentration data of O_3, CO, and NO_2 from four state-controlled monitoring sites in Haikou city during the 13th Five-Year Plan (2016–2020), this paper analyzes the overall characteristics of O_3 pollution and the potential relationship between O_3 and precursor substances. In addition, the monthly and daily variation characteristics of O_3 concentration at the state-controlled monitoring stations were analyzed. Through studying the relationship between O_3 and meteorological factors, the weather types that are prone to trigger O_3 pollution were discussed, providing a reference for O_3 pollution warning and prevention in Haikou city.

2 Metadata of the Dataset

The metadata of Dataset of ozone pollution characteristics and impact factors (2016–2020)[7] dataset is summarized in Table 1. It includes the dataset's full name, short name, authors, year of the dataset, data format, data size, data files, data publisher, data sharing policy, etc.

3 Methods

3.1 Primary Data

The O_3, CO, NO_2, and corresponding meteorological data (air pressure, air temperature, humidity, and wind speed) from 2016 to 2020 used in this research are respectively from 4 state-controlled automatic air quality monitoring stations in Haikou (distribution of stations is shown in Figure 1) and information center of Hainan Meteorological Bureau. Four state-controlled sites respectively: Haida site, Xiuying site, Haishi site, and Longhua site, the state-controlled stations are representative, comparable, and holistic, and can reflect the status of Haikou city air quality more accurately.

3.2 Algorism Principle

The evaluation of monitoring results refers to Environmental Air Quality Standard (GB 3095—2012) and Technical Specification for Environmental Air Quality Evaluation (TRIAL) (HJ 633—2012). The overall pollution characteristics of O_3 in Haikou city from 2016 to 2020 are statistically analyzed based on the average O_3-8h-90PER of 4 stations. CO-95PER and NO_2 are used to analyze the relationship between O_3 concentration and precursors. O_3-8h-90PER and O_3-1h of state-controlled sites are used to study the monthly and daily changes of O_3 pollution, respectively. In addition, Spielman correlation coefficient method and Pearson correlation coefficient method are used for correlation analysis of the relationship between O_3 and precursors and meteorological factors. Correlation coefficient $0.1<|r|\leq 0.3$ is a weak correlation, $0.3<|r|\leq 0.5$ is a moderate correlation, and $|r|>0.5$

is a strong correlation.

Table 1 Metadata summary of the Dataset of ozone pollution characteristics and impact factors (2016–2020)

Items	Description
Dataset full name	Dataset of ozone pollution characteristics and impact factors (2016–2020)
Dataset short name	O3_Haikou2016-202
Authors	Cai, J. Z., Ecological Environmental Protection Administrative Law Enforcement Detachment of Haikou Comprehensive Administrative Law Enforcement Bureau, caijz@haikou.gov.cn Wan, S. H., Haikou Bureau of Ecology and Environment, wangshaohui@haikou.gov.cn Hu, J. X., China Environmental Monitoring Station, hujx@cnemc.cn
Geographical region	Haikou city
Year	2016–2020
Data format	.shp, .xlsx
Data size	33.9 KB
Data files	It consists of 9 data files. (1) geo-location of the sites; (2) monthly concentration data of O_3, CO, and NO_2; (3) monthly and annual O_3 concentration at four monitoring sites; (4) daily variation data of O_3 concentration at four monitoring sites; (5) O_3 concentration, air pressure, air temperature, humidity and wind speed data at four monitoring sites.
Foundation	Haikou Ecological and Environmental Bureau (HXSJ-CG-2021102)
Data publisher	Global Change Research Data Publishing & Repository, http://www.geodoi.ac.cn
Address	No. 11A, Datun Road, Chaoyang District, Beijing 100101, China
Data sharing policy	***Data*** from the Global Change Research Data Publishing & Repository includes metadata, datasets (in the *Digital Journal of Global Change Data Repository*), and publications (in the *Journal of Global Change Data & Discovery*). ***Data*** sharing policy include: (1) ***Data*** are openly available and can be freely downloaded via the Internet; (2) End users are encouraged to use ***Data*** subject to citation; (3) Users, who are by definition also value-added service providers, are welcome to redistribute ***Data*** subject to written permission from the GCdataPR Editorial Office and the issuance of a ***Data*** redistribution license; and (4) If ***Data*** are used to compile new datasets, the "ten percent principal' should be followed such that ***Data*** records utilized should not surpass 10% of the new dataset contents, while sources should be clearly noted in suitable places in the new dataset[8]
Communication and searchable system	DOI, CSTR, Crossref, DCI, CSCD, CNKI, SciEngine, WDS/ISC, GEOSS

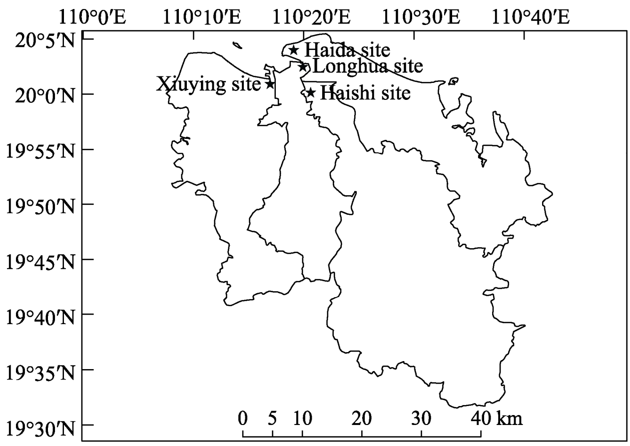

Figure 1 Four air quality monitoring stations in Haikou city

4 Data Results and Validation

4.1 Data Composition

The dataset includes (1) geo-location of the sites; (2) monthly concentration data of O_3, CO, and NO_2 in Haikou from 2016 to 2020; (3) monthly and annual O_3 concentration at four monitoring sites from 2016 to 2020; (4) daily variation data of O_3 concentration at four monitoring sites from 2016 to 2020; (5) O_3 concentration, air pressure, air temperature, humidity, and wind speed data at four monitoring sites. The dataset is archived in .shp and .xlsx data formats; it consists of 9 data files.

4.2 Data Products

4.2.1 Overall Characteristics of O_3 Pollution

Figure 2 shows the monthly changes of O_3-8h-90PER average concentration, CO-95PER, and NO_2 average concentration from 2016 to 2020. It can be seen from Figure 2, that the concentration peaks of O_3 in each year appear from September to December, which is 136, 163, 183, 178, and 156 μg/m^3, respectively. The overall trend of O_3 pollution increased year by year from 2016 to 2019 and decreased in 2020. In addition, the peak of O_3 concentration from 2017 to 2019 exceeded the secondary limit concentration stipulated in the standard, which preliminarily indicated that O_3 pollution in Haikou city was more severe in autumn and winter than in summer. On the one hand, this phenomenon is related to the fact that Haikou is rainy in summer, low solar radiation, and wet deposition are not conducive to O_3 generation[9]. On the other hand, Hainan province may be affected by exogenous transmission, as it is affected by surface cold high pressure control in autumn and winter, the weather situation is stable, and the low-level northerly wind field is controlled, . Under the joint action of local emission and exogenous transport, O_3 concentration increases[10]. In addition, as a tropical monsoon climate with moderate solar radiation intensity and good photochemical reaction, Haikou city boasts the relatively high temperature in autumn and is conducive to the O_3 generation and accumulation. After December, with the intrusion of cold air from northeast, the O_3 concentration decreases, so O_3 concentration reaches the peak from September to December. Compared with other years, the average daily concentration of O_3 in 2016 had the smallest variation range, and its concentration was mainly distributed between 84 and 136 μg/m^3. The concentration of O_3 in 2017 had the largest variation range, and its concentration was mainly distributed between 60 and 163 μg/m^3. Meanwhile, the concentration of O_3 in 2016 and 2020 were below the secondary limit. The O_3 concentration were generally low.

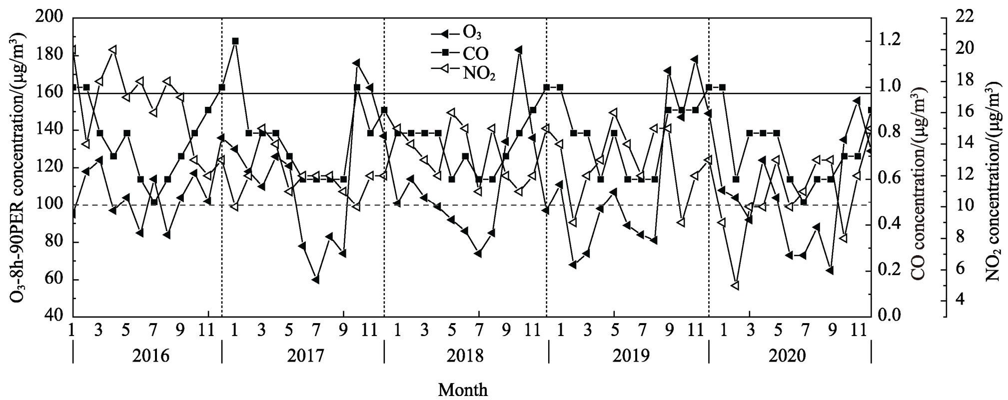

Figure 2 Monthly variations of O_3-8h and CO and NO_2 from 2016 to 2020 (grey dashed line: the primary limit of 100 μg/m^3, black line: the secondary limit of 160 μg/m^3)

Figure 2 shows the correlation coefficient between O_3-8h and the concentration of CO and NO_2. It could be seen that the correlation coefficient between O_3 and CO was 0.552, indicating a strong positive correlation and that between O_3 and NO_2 was −0.14, indicating a weak negative correlation (Table 2). From the view of the monthly average concentration distribution of CO and O_3, CO and O_3 showed positive phase changes in most periods from 2016 to 2020. In 2016, both CO and O_3 had their highest concentration values in December. In 2017–2020, when O_3 concentration increased sharply in October and November, the concentration of CO in the corresponding period also showed an obvious increase. From the perspective of O_3 photochemical formation process, CO is constantly oxidized, so in most cases, CO and O_3 are negatively correlated[11], while Haikou is positively correlated, which is speculated to be related to the pollution degree of air mass[12]. In addition, with the rapid growth of vehicles in Haikou city, a great deal of automobile exhaust emissions make the amount of CO increase, causing pollution to the air environment. The variation trend of O_3 concentration is affected by many factors such as precursor concentration, meteorological conditions, and chemical reactions. In terms of the monthly mean concentration distribution of NO_2 and O_3, they showed negative phase change in all months except February and March in 2016, negative phase change in most periods from 2017 to 2020, and positive phase change in a short period in summer. In Hainan province, because of high summer temperature and sufficient sunshine duration, photochemical reactions occur under the influence of strong solar radiation, so O_3 concentration usually reaches the annual maximum value[13]. However, summer in Hainan province is the primary flood season with abundant rainfall. The erosion of rain and high relative humidity both inhibit the photochemical reaction to some extent and weaken the influence of NO_2 and O_3, so O_3 concentration does not reach the maximum in summer[14,15]. In addition, when the concentration of CO and NO_2 reached a relatively stable plateau, O_3 concentration still fluctuated, which reflected the complexity of factors influencing O_3 concentration change in Haikou city. The precursor could not fully represent the occurrence of O_3 pollution, so it was necessary to further analyze the temporal variation characteristics of O_3 concentration and the influence of meteorological factors.

Table 2 The correlation coefficient between O_3-8h concentration and precursor concentration in 2016–2020

Category	Correlation index	*p* value
O_3-CO	0.552	$p<0.01$
O_3-NO_2	−0.14	$p>0.05$

The monthly mean concentration of O_3-8h-90PER for the Haida site, Xiuying site, Haishi site, and Longhua site during 2016–2020 were statistically analyzed, and the outline diagram of the O_3 concentration of each station was drawn with the maximum, minimum, and average values as characteristic values (Figure 3). In our study, the average values of the maximum O_3 concentration at the Haida site, Xiuying site, Haishi site, and Longhua site were 105, 85, 94, 109, 92 μg/m^3, and the average values of the minimum O_3 concentration were 53, 36, 31, 36, 31μg/m^3, respectively. The O_3 concentration were 74, 62, 55, 64, and 60 μg/m^3 by average analysis of the average values of each site. As can be seen from the above O_3 concentration data, compared with developed areas such as Guangdong and Chengdu province, the O_3 pollution level in Haikou city had not reached a significantly high pollution

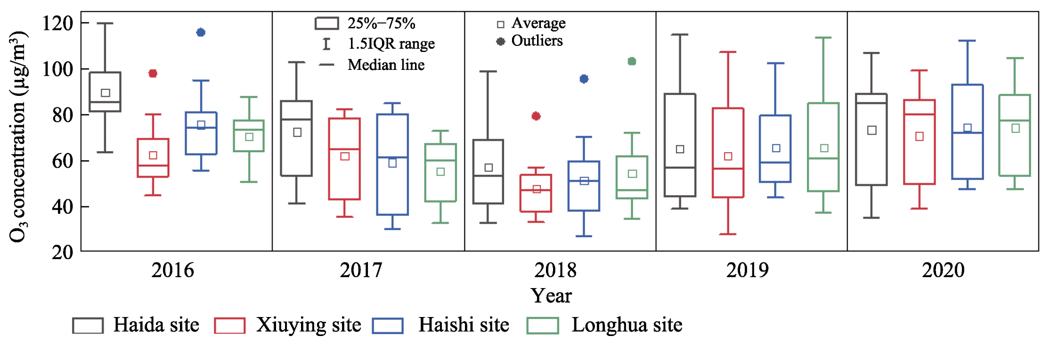

Figure 3 2016–2020 annual average O_3 concentration of four urban testing sites

level[15,16,17]. According to the analysis of the O_3 concentration of the four sites, the Haida site was in the high-value area in 2016, while the Xiuying site was in the low-value area. From 2017 to 2020, the high-value area and the low-value area were no longer noticeable, indicating that the area scope of O_3 pollution in the urban area of Haikou was expanding.

4.2.2 Time-varying Characteristics of O_3 Concentration

4.2.2.1 Monthly Variation Characteristics of Point Position

Figure 4 shows the monthly variation of the mean concentration of O_3-8h-90PER at state-controlled monitoring sites from 2016 to 2020. According to the spring (March to May), summer (June to August), autumn (September to November), and winter (December to the next February) classification. It could be seen that the seasonal variation of O_3 was apparent. The peak value of O_3 concentration at the four sites occurred frequently in October-December (autumn and winter), in which the average maximum value of O_3 in 2016 and 2017 appeared in December, the average maximum value of O_3 in 2018 appeared in October, and the average maximum value of O_3 in 2019 and 2020 appeared in November. This is consistent with the time range of the peak O_3 concentration in Haikou city from 2016 to 2020. This is different from cities with severe air pollution in China. For example, O_3 concentration in Guangdong and Shanghai in summer is higher than that in autumn and winter[15,16,18,19]. The high concentration of O_3 in Haikou city in autumn and winter was mainly due to the northeast wind in winter, which was easily affected by inland pollution transport. Besides, the temperature in autumn was not low, and the photochemical reaction conditions were good, which was conducive to the generation of O_3[5].

In addition, Haikou city has frequent typhoons in October, and the pollutants are not easy to diffuse under the action of external downdraft. Further analysis found that in July 2016 and May 2017—each site's O_3 concentration was on a decline trend, August 4, 2020—a downward trend, refer to the corresponding climate data showed that during the period while the temperature was higher, the Haikou city was mainly influenced by the southwest monsoon, clean air from the ocean of air dilute the atmosphere in Haikou city. The regional climate difference was the main reason why the time distribution of O_3 in Haikou was different from that in inland cities. It can also be seen from Figure 4, that O_3 in January-February 2016 was in a rising stage, while all other years were in a declining stage. O_3 concentration in January-March 2019 was lower than that in other years, indicating that it was necessary to deal with O_3 spring pollution in advance.

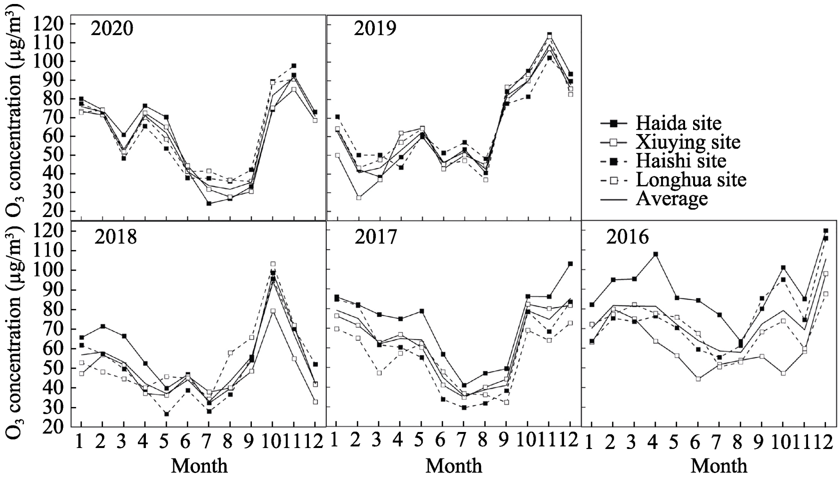

Figure 4 Monthly variations of O_3 average concentration at national monitoring sites from 2016 to 2020

In addition, O_3 from August to October 2016 to 2020 presented a trend of aggravation, with a significantly higher growth rate than in other months, further highlighting the severity of the pollution situation in autumn, indicating that this period was the key period for O_3 pollution prevention and control.

4.2.2.2 Diurnal Variation Characteristics of Point Position

Figure 5 shows the diurnal variation of O_3-1h mean concentration at the state-controlled monitoring sites from 2016 to 2020. It could be seen that the variation characteristics of O_3 concentration at the four stations were single-peak type, and the maximum O_3 concentration from 14:00 to 16:00 throughout the day, which was similar to the diurnal variation pattern of O_3 concentration in other cities in China[20,21]. This variation was due to the daily budget mechanism of O_3 and was related to the photochemical reaction rate and atmospheric diffusion capacity. The concentration of O_3 from 00:00 to 8:00 showed a trend of continuous decline and decreased to the lowest value at 8:00, with a trough value. This is because the anthropogenic activities weakened during this period, the emissions of precursor substances decreased, the night temperature was low, and the photochemical reaction was almost zero. O_3 is mainly consumed, and its budget is negative, so it remains in the range of low concentration value. The concentration of O_3 from 8:00 to 16:00 showed a trend of continuous rise and reached the peak concentration in a day. This is because the solar radiation intensity keeps increasing after sunrise, and the temperature gradually rises. In addition, the concentration of O_3 precursor produced by transportation sources, industrial sources, and biological sources increases, and the photochemical reaction rate increases. After 16:00, O_3 concentration gradually returned to the low range; this is mainly due to the solar radiation after 16:00 started to wane, vertical mixing, horizontal divergence strengthened and weakened photochemical reaction, and NO peak emissions during rush hour consumes O_3, the accumulation of the O_3 return to give way to consumption function, with balance negative. Then a concentration decreases continuously, and the cycle continues[17,22]. In addition, the overall level of O_3 daily concentration in 2019 was higher than that in other years, which may be related to the strengthening of urban emissions and meteorological conditions.

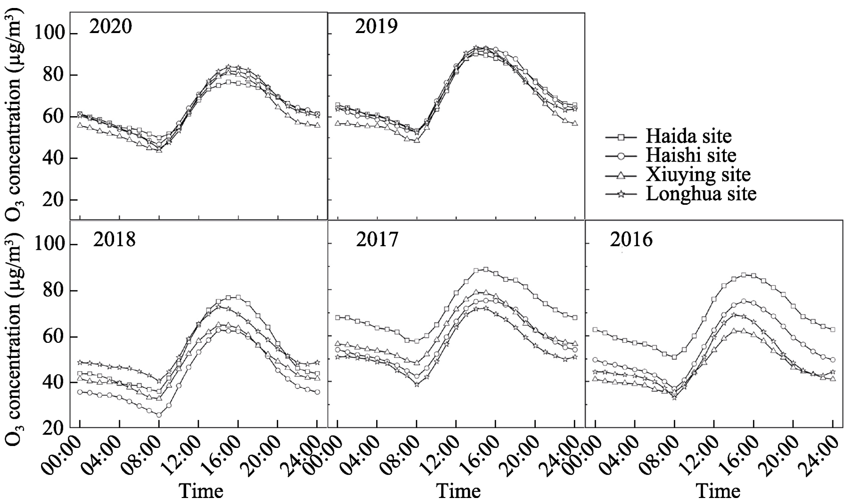

Figure 5 Daily variations of O_3 average concentration at national monitoring sites from 2016 to 2020

4.2.3 Influence of Meteorological Factors on Typical O_3 Pollution Days

Meteorological factors can affect the formation, transmission, settlement, and dissipation of O_3. Based on the analysis of the above results, it could be known that the high-incidence period of O_3 pollution in Haikou city was autumn and winter (September to December). To better study the relationship between O_3 concentration and meteorological factors, the O_3-8h concentration data and meteorological factor data of the same period from September to

December 2016 to 2020 from four state-controlled monitoring stations were selected for analysis, and the correlation coefficients between O_3-8h and various meteorological factors were calculated (Table 3). The characteristics of meteorological factors that easily trigger O_3 pollution weather in Haikou city were obtained.

Table 3 Correlation coefficient between O_3 and various meteorological factors

	O_3-pressure		O_3-temperature		O_3-humidity		O_3-wind speed	
Monitoring site	Correlation index	*p* value	Correlation index	*p* value	Correlation index	*p* value	Correlation index	*p* value
Haida site	0.398	$p>0.05$	0.417	$p>0.05$	−0.539	$p<0.05$	0.630	$p<0.01$
Haishi site	0.216	$p>0.05$	0.374	$p>0.05$	−0.170	$p>0.05$	0.327	$p>0.05$
Longhua site	0.244	$p>0.05$	0.032	$p>0.05$	−0.425	$p>0.05$	0.454	$p<0.05$
Xiuying site	0.553	$p<0.01$	0.193	$p>0.05$	−0.622	$p<0.01$	0.297	$p>0.05$

4.2.3.1 Influence of Air Pressure and Temperature on O_3 Pollution

Figure 6 shows the changes of ozone and air pressure, and temperature at national monitoring sites. It can be seen that O_3 concentration in Haikou is positively correlated with air pressure and temperature. Quantitative analysis of the relationship between them (Table 2) showed that the correlation coefficient between O_3 concentration and air pressure is positive. However, only the positive correlation at the Xiuying site passed the significance test ($p<$ 0.01), and the correlation between O_3 concentration and air pressure was weak at other three stations. The correlation coefficient between O_3 concentration and the air temperature was positive, but the correlation coefficient between O_3 concentration and air temperature at four stations did not pass the significance test ($p>0.05$). Haikou city is located at the tropical edge of low latitude and has a tropical maritime monsoon climate. It is cool in autumn, and the temperature is lowerthan that in spring and summer. In winter, due to the southward extension of the continental cold air mass, there often invades cold airflow, which indicates that the main meteorological factors affecting the change of O_3 concentration in Haikou city from September to December are not atmospheric pressure and temperature.

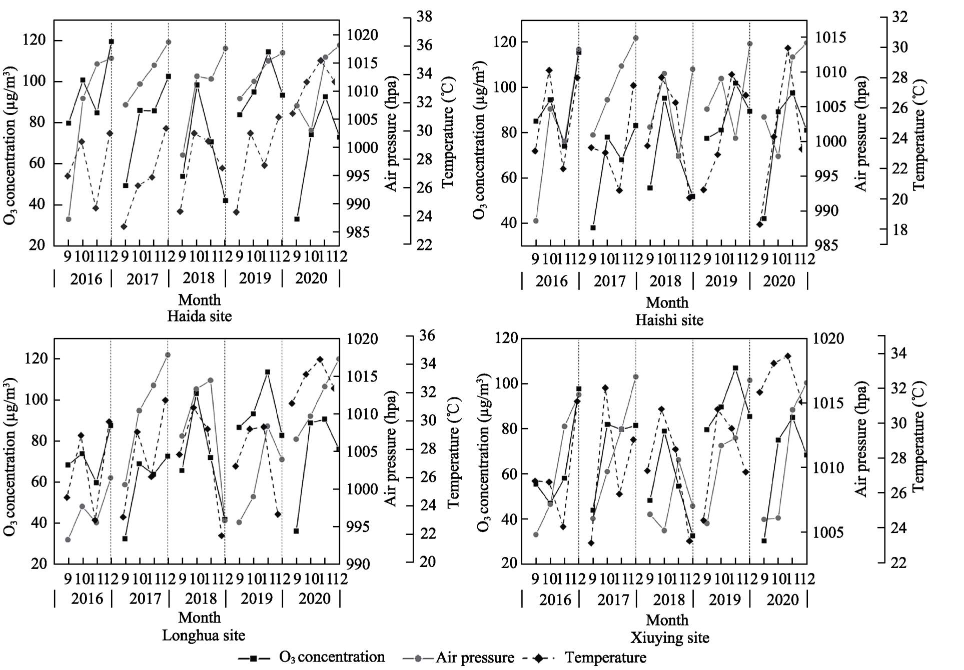

Figure 6 Changes of ozone and air pressure and temperature at national monitoring sites

4.2.3.2 Influence of Humidity and Wind Speed on O_3 Pollution

Figure 7 shows the change of O_3 concentration, humidity, and wind speed at the state-controlled monitoring site. It could be seen that O_3 concentration was negatively correlated with humidity and positively correlated with wind speed. Quantitative analysis of the relationship between O_3 concentration, humidity, and wind speed (Table 2) manifested that the correlation coefficient between O_3 and humidity at all monitoring stations was negative. There was a significant negative correlation between O_3 concentration and humidity at the Haida site ($p<0.05$), while there was a strong negative correlation between O_3 concentration and humidity at the Xiuying site ($p<0.01$).The correlation coefficients between O_3 and wind speed at all monitoring stations were positive. There was a significant positive correlation between O_3 concentration and wind speed at the Longhua site ($p<0.05$) and a strong positive correlation between O_3 concentration and wind speed at the Haida site ($p<0.01$). It indicated that from September to December, the change of O_3 concentration in Haikou city was more likely to be negatively affected by humidity and positively affected by wind speed.

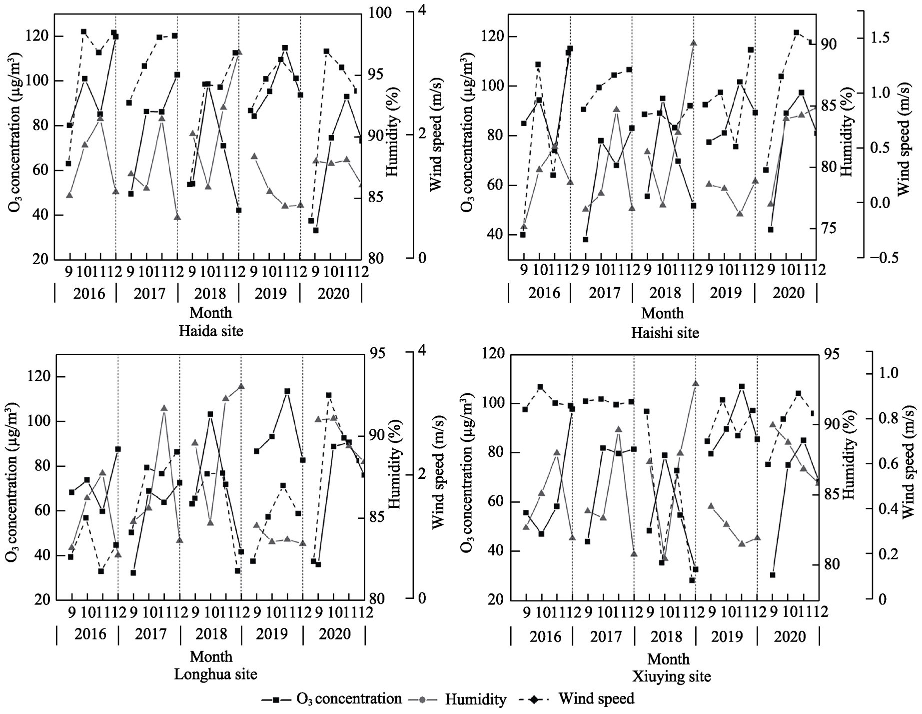

Figure 7 Changes of ozone and wind speed and humidity at national monitoring sites

Haikou is prone to heavy rain in autumn and sometimes cloudy in winter, so the O_3 concentration and humidity trend in Haikou is opposite from September to December. Wind speed can reflect pollutant transport efficiency and removal efficiency[23]. The increase of wind speed has dual effects on O_3 concentration, which occurs simultaneously. Firstly, the air mass transport power increases, the height of the atmospheric boundary layer increases and the vertical momentum transport is enhanced, all that are conducive to the transmission of O_3 from the upper region to the ground. When accumulation remains dominant in local areas, the concentration of O_3 will increase. Secondly, the horizontal diffusion effect is enhanced. When it is dominant, the increase of wind speed accelerates O_3 dilution[24]. When the wind speed decreases, its scavenging effect on O_3 is limited, and the cumulative effect is dominant, increasing the concentration of O_3[25]. It can be seen from Figure 8 the wind speed monitored by the four state-controlled sites from September to December 2016–2020 ranges from 0.1 to 3.8 m·s^{-1}. The wind speed was low, and the vertical downward transport effect of O_3 was stronger than the horizontal diffusion effect, which was conducive to the accumulation of O_3. Therefore, there is a positive correlation between O_3 concentration and wind speed in Haikou from September to December. On the basis of strengthening the existing pollution prevention and control in Haikou city, strengthening joint prevention and control with upper-level regions is the key to effectively control O_3 secondary pollution.

To sum up, in autumn and winter (September to December) when O_3 pollution occurs frequently, the influence of meteorological factors on O_3 concentration is in the following order—humidity > wind speed > air pressure > temperature. It indicated that humidity and wind speed were the main meteorological factors affecting O_3 pollution in Haikou city in autumn and winter. On the whole, low humidity and low wind speed were prone to O_3 pollution. The change of O_3 concentration was affected by many factors, such as precursors, atmospheric fine particles, and meteorological factors, and the changing process was a complex and comprehensive interaction process. Therefore, the influence of meteorological factors on O_3 concentration was inevitably affected by other non-meteorological factors and the interaction between meteorological factors. Consequently, in the study of O_3 pollution characteristics and meteorological impact, to improve the accuracy of O_3 pollution prevention and control in Haikou city, we must consider the role of various possible factors, adjust pollution prevention and control strategies timely, and strengthen the cooperative control of multiple regions.

5 Discussion and Conclusion

(1) From 2016 to 2020, the peak occurrence period of O_3 concentration in Haikou city is significantly different from other inland cities, mainly appearing in autumn and winter, from October to December. Regional climate difference is the main reason for the different time distribution of O_3 in Haikou from that in inland cities.

(2) The diurnal variation of O_3 concentration presents a prominent single-peak characteristic, with a trough value at 8:00 and a peak value from 14:00 to 16:00. According to the characteristic value of O_3 concentration, the scope of O_3 pollution in urban areas has gradually expanded and worsened in recent years.

(3) O_3 concentration is positively correlated with CO concentration and wind speed, negatively correlated with humidity. Air pressure and temperature are not the main meteorological factors affecting O_3 concentration change in Haikou city in autumn and winter .

(4) In line with the feature of O_3 pollution in Haikou city, a series of measures have been taken, such as stimulating the purchase of new energy vehicles, encouraging the district government and relevant departments to establish a responsibility system, industrial enterprises to implement a staggered rush hour production plan and motor vehicle peak shifting travel, improving pollution prevention and control measures of the third service catering enterprises , strengthening the environmental monitoring and supervising capacity, promoting joint prevention and control with upper-level regions. O_3 pollution in Haikou city is expected to be improved.

Author Contributions

Cai, J. Z. designed the algorithms of the dataset. Wang, S. H. contributed to the data collecting and processing. Hu, J. X. wrote the data paper.

Conflicts of Interest

The authors declare no conflicts of interest.

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