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Shifting patterns of Ozone Season due to policy and human activity in Beijing between 2013 and 2023

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Abstract: Since 2013, Beijing has implemented a series of stringent measures to control air pollution, resulting in significant improvements in air quality. This study analyzed the variations in ozone pollution in Beijing over the past decade, focusing on the influence of human activities and environmental management policies from 2013 to 2023. Over this period, the duration of the Ozone Season in Beijing has prolonged, with the onset of ozone pollution occurring earlier and its cessation extending later during the year. Additionally, there has been a rise in the low percentile concentrations of the maximum 8-hour moving average of ozone (MDA8), and the overall exposure time to ozone has shifted to later over the years. While diurnal peak concentrations during the Ozone Season have decreased, trough concentrations have increased, resulting in a more subdued diurnal variation. Furthermore, both the maximum generation and consumption rates of ozone have decreased in absolute terms, with the maximum generation rate showing a tendency to occur earlier in the day. To better protect human health and enhance the effectiveness of environmental policies, it is essential to closely monitor the evolving patterns of urban ozone pollution.

Keywords: Ozone Season, exposure time, generation rate, ozone percentile concentration, diurnal variation.

Highlights:

1. The Ozone Season in Beijing prolonged.
2. Summertime ozone exposure extends into the nighttime.
3. Both diurnal production and destruction rates dropped

1.Introduction

Urban ozone poses a significant threat to public health, with long-term exposure to elevated ground-level ozone increasing the risks of respiratory, cardiovascular, and other diseases(Nuvolone et al., 2018; Crouse et al., 2015; Zhang et al., 2019; Wang et al., 2020b; Liu et al., 2018). Ozone formation is influenced by precursor pollutants, including volatile organic compounds (VOCs) and nitrogen oxides (NOx), primarily originating from urban industrial and traffic emissions. Climate conditions also play a crucial role in long-term ozone trends.(Sitch et al., 2007; Bais et al., 2018; Bernhard et al., 2023).

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Beijing, the capital of China, is located in the northern North China Plain and has a population of nearly 22 million. As a major northern megacity and international metropolis, environmental quality in Beijing has garnered substantial attention. (Huang et al., 2017; Qiang and Hu, 2022; Li et al., 2020; Streets et al., 2007). Since 2013, the city has implemented comprehensive governance measures to combat air pollution(Li et al., 2020; Wen et al., 2021; Wang et al., 2023), achieving significant results acknowledged by the United Nations Environment Programme as the "Beijing Miracle." (Programme, 2019) However, improvements in ozone concentrations have been less pronounced than those for other pollutants like PM2.5, and the interannual variability of ozone levels suggests that addressing ozone pollution presents greater challenges.

Amid these pollution control efforts, notable changes in the volume and composition of atmospheric pollutant emissions have occurred in Beijing and its surroundings(Zhang et al., 2016; Xue et al., 2020; Li et al., 2017; Wu et al., 2023). Thus, examining ozone variations over the past decade is critical for evaluating the effectiveness of these measures.

Previous research on ozone in Beijing has primarily focused on the summer months(Xu et al., 2011; Wang et al., 2020a; Zhang et al., 2021; Zhao et al., 2018), despite ozone pollution occurring year-round, typically from March to October, with notable activity in spring and autumn(Chen et al., 2019; Wang et al., 2020c; Wang et al., 2015).. Given the substantial interannual variability in ozone levels, analyzing long-term trends can enhance our understanding of overall changes in ozone concentrations. This study introduced the concept of the Ozone Season to differentiate periods of concentrated ozone pollution across various years and to facilitate analysis of its long-term trends.

The Ozone Season was first defined in North American studies(Cox and Shao-Hang, 1996), where it was identified as June to September for northern cities and May to October for southern cities. Notably, Carl (Cardelino et al., 2001)indicated that the typical Ozone Season in the U.S. spans early May to the end of September, while Qin(Qin et al., 2004) defined it for Southern California as June to October. In China, studies have generally referred to the warm season (April to September) in analyzing ozone pollution(Lu et al., 2020; Li et al., 2021b; Gao et al., 2021). However, due to regional variations, the duration of ozone pollution differs. In northern cities of China, ozone pollution typically occurs from April to September, whereas in southern cities like Guangzhou and Chengdu, it may extend to October or even November and December(Wang et al., 2017; Li et al., 2021a; Wang et al., 2022). As a result, the warm season does not fully encompass ozone pollution events across different areas. Thus, the Ozone Season is defined as the months when ozone generation is most active, making it more suitable for studying regional characteristics of ozone pollution.

According to China's Ecological Environment Department, a day is designated as an ozone pollution day when the 8-hour moving average (MDA8) exceeds 160 μg m^{-3}(生态环境部, 2012). Based on this standard, this study defined the Ozone Season as the period from the first to the last MDA8 pollution event. Utilizing ground-level ozone monitoring data from Beijing between 2013 and 2023, this research examined changes in the Ozone Season and the long-term trends in ozone generation and consumption, evaluating the impact of pollution control strategies on ozone pollution.

2. Data and methods

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2.1 Data instruction

This study utilized daily and hourly ozone data from Beijing for the period 2013 to 2023, obtained from the Beijing Municipal Ecological and Environmental Monitoring Center (http://zx.bjmemc.com.cn/timestamp=1693966844922). Ozone concentrations were measured using the Thermo-Fisher 49C ozone analyzer, which employs ultraviolet photometry to convert measurements into standard mass concentration units (μg m^{-3}). Data was collected from 23 national monitoring stations strategically located to represent densely populated urban and suburban areas. Hourly ozone levels for the city were calculated as the arithmetic mean of measurements from these stations, with the maximum 8-hour moving average (MDA8) derived from the highest hourly values. All measurements complied with the environmental air quality standards (GB3095-2012) established by China's Ministry of Ecology and Environment.

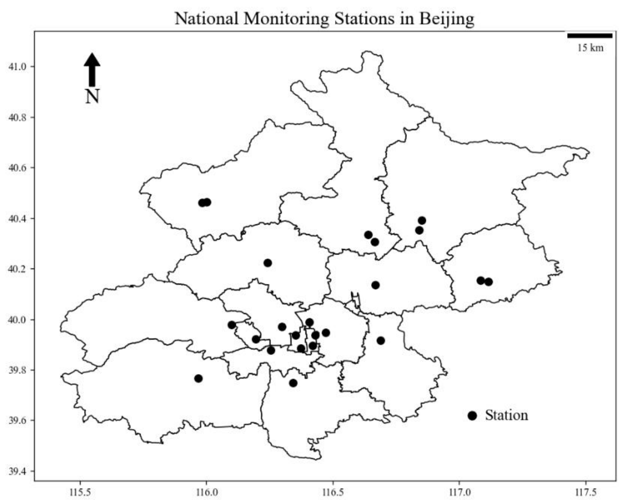

Figure 1 Spatial distribution of Beijing stations

2.2 Research methods

According to the standards set by China's Ministry of Ecology and Environment, days when the daily maximum 8-hour average (MDA8) exceeded 160 μg m^{-3} were classified as ozone pollution days. This research analyzed the trends in the first and last pollution days to determine the duration of the Ozone Season based on the interval between these two dates. Additionally, the study examined ozone level changes on typical pollution days over the past decade to understand shifts in ozone generation and consumption in Beijing.

Typical ozone days were selected to evaluate the impact of specific weather events, such as precipitation, strong winds, or overcast conditions, on daily ozone levels. Days with more than 0 mm of precipitation or wind speeds exceeding 5 m/s for more than two hours were excluded from the analysis. After adjusting to weather effects, the proportion of typical ozone days during the Ozone Season from 2013 to 2023 ranged from 54.3% to 76.7%. The year 2021 recorded the shortest Ozone Season and the lowest effective data rate after accounting for weather exclusions.

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By utilizing the remaining hourly ozone data, trends in typical diurnal variations in ozone levels were analyzed over the years

Table 1 Proportion of effective typical ozone days in Ozone Season from 2013 to 2023

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Valid days	72	111	95	107	91	115	123	107	63	135	131
Total days	130	166	159	150	135	167	168	166	116	176	180
Effective rate（%）	55.4	66.9	59.7	71.3	67.4	68.9	73.2	64.5	54.3	76.7	72.8

3. Results and discussion

3.1 Changes in the Ozone Season in Beijing

Over the past decade, the date of the first pollution event has shifted to an earlier time in the year. Figure 2 illustrates the variations in the Ozone Season in Beijing from 2013 to 2023. Here, FPD denotes the first ozone pollution day of the year, marking the beginning of the Ozone Season, while LPD represents the last ozone pollution day, indicating the season's conclusion. The secondary axis displays the duration of the Ozone Season. Analysis shows that this event typically occurs between March and May. In 2023, the earliest date was March 30, while in 2021, the latest occurrence was on May 16. April has the highest frequency of first pollution days, totaling seven days, which accounts for 66% of all recorded pollution days. May follows with three days, and only one day was recorded in March. This trend reveals that the date of the first pollution event has advanced from May 5, 2013, to March 30, 2023, indicating an average shift of 38 days over 11 years, or approximately 1.38 days earlier each year.

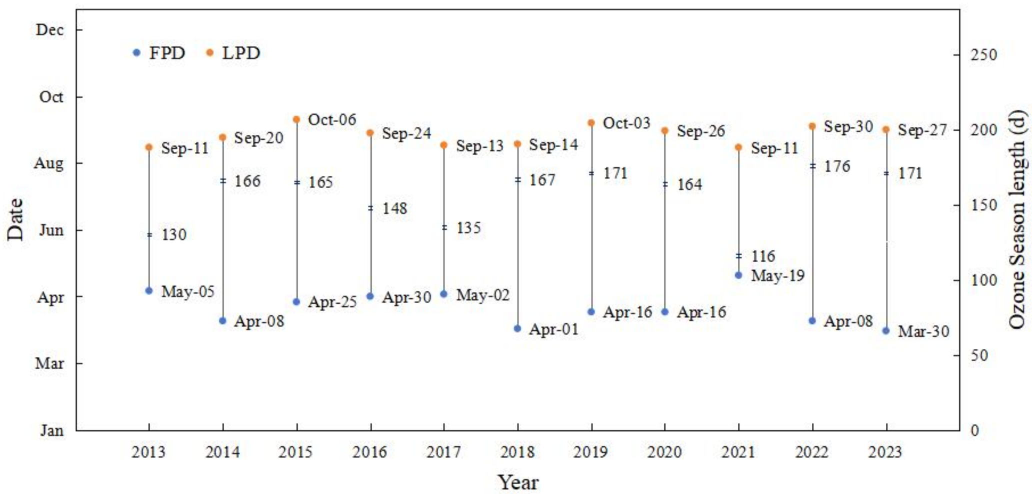

Figure 2 Changes in Beijing Ozone Season from 2013 to 2023

In contrast, the date of the last pollution event in Beijing has been delayed over the same period. The final pollution occurrences are recorded between September and October, with the

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earliest date on September 11, 2013, and the latest on October 6, 2015. Unlike the first pollution days, there is significantly less variability in the timing of the last pollution days, with 88% occurring in September. The last pollution date has been postponed from September 11, 2013, to September 27, 2023, representing a delay of 16 days and an average trend of 0.63 days per year, which is slower than the trend observed for the first pollution event.

Furthermore, the duration of the Ozone Season in Beijing has increased over the past decade. This season, defined as the interval between the first and last pollution days. It has ranged from 116 to 176 days, with an average length of 155 days. The length of the Ozone Season has varied significantly from year to year, with 2021 being the shortest and 2022 being the longest. The earlier occurrence of the first pollution event and the later occurrence of the last pollution event have collectively extended the Ozone Season by an average of 2.0 days per year, which represents approximately 1.3% of the average season length.

Currently, international research has primarily focused on the characteristics of ozone concentration(Chen et al., 2020; Yin et al., 2017; Cao et al., 2024), with insufficient studies addressing the long-term changes in the duration of the Ozone Season. As the Ozone Season represents a period of heightened ozone pollution, its extension poses additional health risks to the population, necessitating greater attention to the impacts of ozone over extended periods. The prolongation of the Ozone Season may be linked to climate change and alterations in pollutant emission patterns(Schnell et al., 2016; Doherty et al., 2013; Sicard, 2021).

3.2 Changes in MDA8 percentile concentrations in Beijing

To examine the distribution characteristics of MDA8 concentrations across different years, box plots for the period from 2013 to 2023 were generated. Fig. 3 illustrates the minimum, 25th percentile, mean, median (50th percentile), 75th percentile, and maximum distributions of MDA8 for each year. The mean MDA8 concentrations fluctuated between 85 and 111 μg m^{-3}, with the lowest recorded in 2013 and the highest in 2023. This demonstrates considerable year-to-year variability and an overall upward trend, averaging an increase of 0.94 μg m^{-3} per year. Notably, the outlier year of 2021 had a mean concentration of 87 μg m^{-3}, representing the second lowest value during this period.

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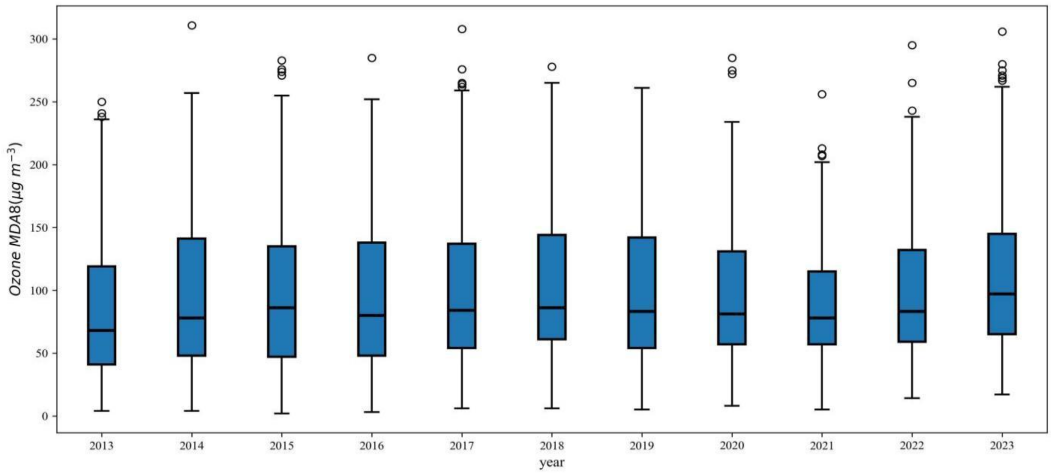

Figure 3 Beijing day MDA8 box diagram from 2013 to 2023

Over the past decade, the lower percentile concentrations of MDA8 in Beijing have also increased. Specifically, the minimum MDA8 concentrations rose from 4 μg m^{-3} in 2013 to 14 μg m^{-3} in 2023, reflecting a growth of 225% with an average increase of 1.11 μg m^{-3} per year. Similarly, the 25th and 50th percentile MDA8 concentrations increased by 24 μg m^{-3} and 31 μg m^{-3}, respectively, with growth rates of 1.94 μg m^{-3} per year and 1.30 μg m^{-3} per year. This rise in lower percentile concentrations suggests an increase in background ozone levels and an enhancement of atmospheric oxidizing capacity.

In contrast, high percentile MDA8 concentrations have exhibited no significant changes over the years. The maximum MDA8 concentration recorded was 311 μg m^{-3} in 2014, while the minimum was 256 μg m^{-3} in 2021. Fluctuations in the maximum and 75th percentile MDA8 concentrations demonstrated weak trends over time, likely influenced by substantial variability in meteorological conditions. Notably, the 90th percentile MDA8 concentration has shown a declining trend of approximately -2.45 μg m^{-3} per year. The correlation of changes in high-percentile ozone concentrations over the years has been relatively weak, possibly due to the significant impact of interannual meteorological fluctuations on high ozone values. This results in less pronounced long-term trends compared to lower concentration percentiles.

Recent studies have indicated that low percentiles (below the 25th percentile) of ozone concentrations have increased globally across all regions, while high percentiles (above the 75th percentile) have decreased in North America and Europe, with an overall increase noted in the Southern Hemisphere and Japan(Christiansen et al., 2022). Yan's research (Yan et al., 2018) also identified an increase in the 5th percentile of ozone concentrations in Europe, alongside a rise in the 95th percentile. Chen's study(Chen et al., 2020) on Beijing reported an upward trend in the 10th and 25th percentile low concentrations since 2013, aligning with these global findings. However, changes in high-percentile concentrations in Beijing were found to be insignificant. As many studies have suggested, the observed rise in low percentile concentrations across various global regions may be linked to decreased emissions of ozone precursor substances, along with contributions from high-altitude ozone transport. The overall increase in average concentrations

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may indicate a worsening trend in ozone pollution, potentially connected to broader global climate changes that enhance ozone transport and create more favorable conditions for ozone generation under higher temperatures.

3.3 Changes in ozone exposure time in Beijing

In recent years, urban ozone pollution has posed a persistent threat to human health, with the maximum daily average of ozone (MDA8) during the warm season widely used to assess outdoor ozone exposure levels(Lu et al., 2018; Niu et al., 2022; Byun et al., 2022). Analyzing the temporal distribution of ozone MDA8 over the course of a day (referred to as ozone MDA8 duration or exposure time, denoted as t1, t2, ..., t8) can effectively provide health risk warnings for sensitive populations.

Fig. 4 reveals significant differences in ozone exposure time (T_MDA8) between the cold and warm seasons in Beijing. From November to January, the ozone exposure period ranges from 11:00 to 19:00. As temperatures rise, this exposure window shifts, with the duration extending from 14:00 to 21:00 during the months of April to September. This indicates that populations are exposed to elevated ozone levels even during nighttime in the warm season.

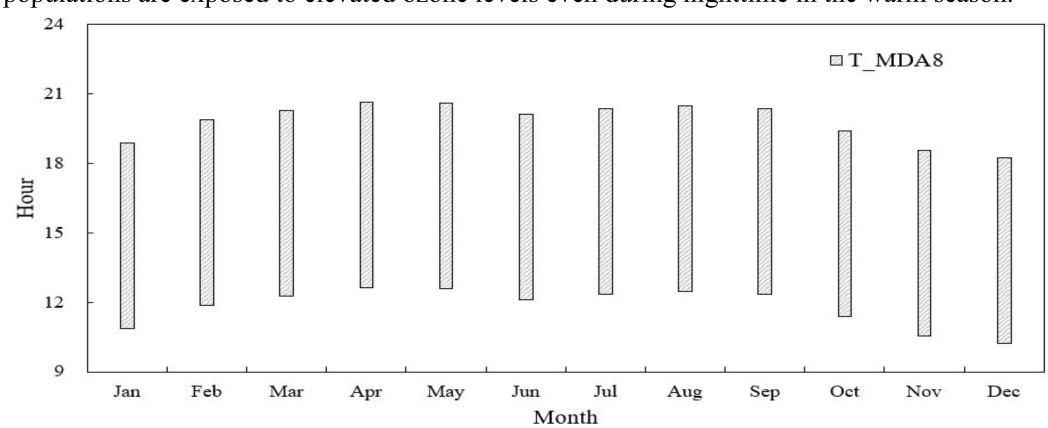

Figure 4 Average duration of MDA8 ozone in Beijing by month from 2013 to 2023

Over the years, there has been a noticeable trend of delayed ozone exposure times during the cold season (October to March). The starting time (t1) of ozone exposure shifted from primarily occurring between 10:00 and 11:00 in 2013 to a new window of 12:00 to 13:00 by 2023, indicating a postponement in the occurrence of high-concentration ozone during the cold season, as shown in Fig. 5. A similar trend is observed in the warm season, where the starting time (t1) shifted from 11:00-12:00 in 2013 to 12:00-13:00 in 2023. However, this delay is less pronounced compared to that in the cold season, as shown in Fig. 7a.

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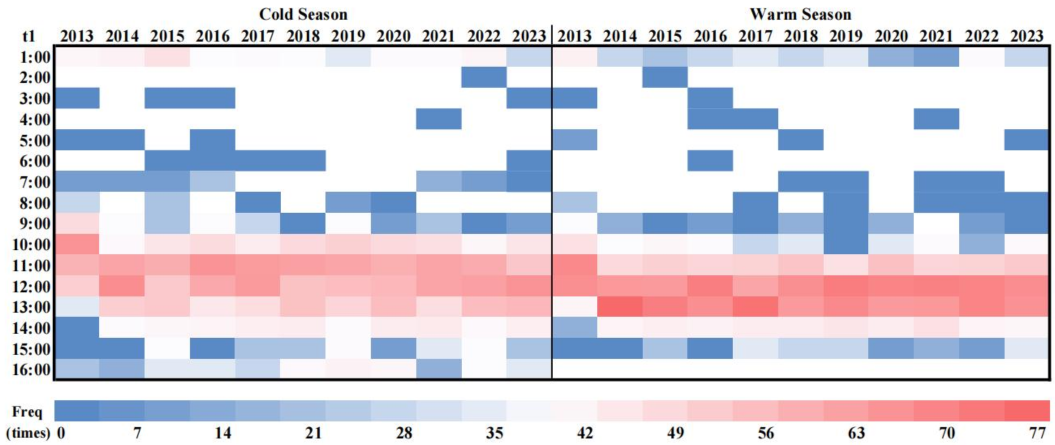

Figure 5 Variation in ozone exposure times（t1）during the cold season and warm season from 2013 to 2023. The heatmap characterizes the frequencies of t1 occurrences at different times over these years.

This postponement of ozone exposure times suggested a delay in the generation of high ozone levels over the years, which may extend the impact on human health into the nighttime hours. Currently, there is a lack of long-term studies on ozone exposure times in China. The variations in ozone exposure time in Beijing were influenced by changes in local ozone generation characteristics, highlighting the importance of understanding these dynamics for evaluating the effectiveness of pollution control policies in addressing ozone levels in the city.

There were significant differences in ozone exposure times between pollution days(MDA8 exceeds 160 μg m^{-3}) and non-pollution days. Because the number of pollution days in a year is much lower than that of non-pollution days, we normalized the frequency distribution to obtain normalized frequencies (expressed as a percentage), as shown in Fig.6. On pollution days, the starting time (t1) of ozone exposure ranges from 11:00 to 16:00, with a peak occurring between 13:00 and 14:00. In contrast, on non-pollution days, the starting time (t1) spans from 1:00 to 16:00, with the majority occurring between 10:00 and 15:00. This indicates that ozone exposure time on pollution days is more concentrated, primarily occurring from the afternoon to the evening. This time frame is critical for implementing protective measures for sensitive populations.

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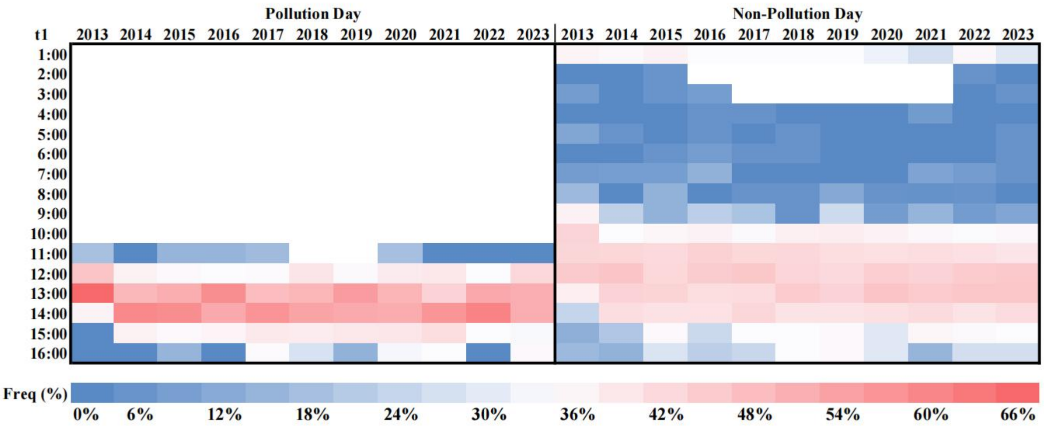

Figure 6 Variation in ozone exposure times (t1) on pollution and non-pollution days from 2013 to 2023. The heatmap characterizes the normalized frequencies of t1 occurrences at different times over these years.

Over the years, there has been a noticeable delay in the starting time (t1) of ozone exposure on non-pollution days, shifting from 10:00-12:00 in 2013 to 11:00-14:00 in 2023. In contrast, changes in t1 on pollution days are relatively minor, as shown in Fig.7b. This may be attributed to the significant influence of meteorological factors, particularly temperature, on ozone generation during pollution days. Since pollution days predominantly occur in the warm season, the timing of high temperatures tends to be more consistent, resulting in a more fixed ozone generation period.

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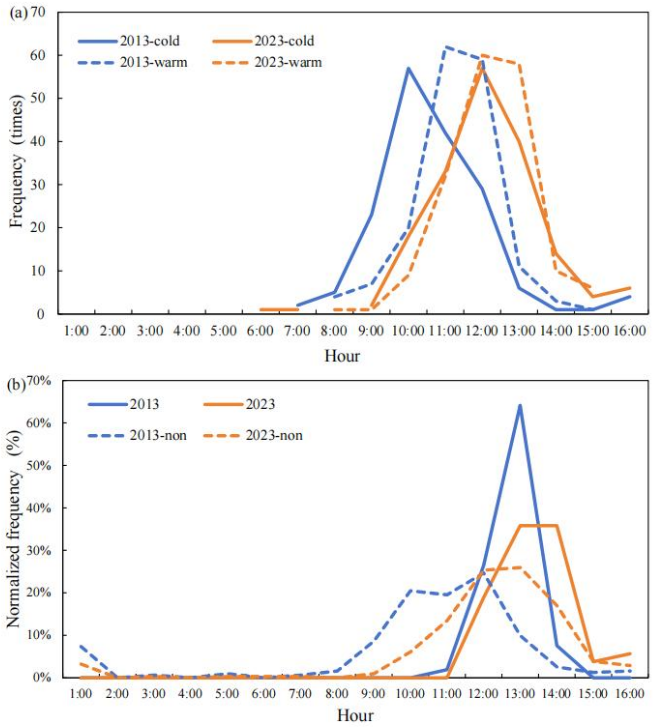

Figure 7 Distribution frequencies of t1 in cold season and warm season for 2013 and 2023(a), and distribution normalized frequencies of t1 in pollution days and non-pollution days(b)

3.4 Diurnal variation of Ozone Season in Beijing

Based on hourly ozone data with meteorological influences removed during the Ozone Season, typical diurnal variation patterns of ozone from 2013 to 2023 were analyzed. Each year's diurnal variation in ozone levels displayed a clear unimodal pattern. It began at 01:00 with decreasing ozone concentrations, reaching a low point between 06:00 and 07:00. The levels then rose to a peak occurring between 16:00 and 18:00, followed by a decline, as shown in Fig. 8a and 8b).

The analysis revealed a decreasing trend in peak ozone concentrations, accompanied by a delay in their occurrence. In contrast, trough concentrations showed an increasing trend, which occurred earlier over the same period. From 2013 to 2023, peak ozone concentrations during the Ozone Season ranged from 137.8 to 184.5 μg m^{-3}, with a declining trend in diurnal peak values at a rate of 3.6 μg m^{-3} per year. Peak values typically occurred between 16:00 and 18:00, with a noticeable delay over the years. Between 2013 and 2020 (excluding 2017), peak concentrations were consistently recorded at 16:00, whereas from 2021 to 2023, they shifted to between 17:00 and 18:00. Trough values ranged from 23 to 42 μg m^{-3}, exhibiting an increasing trend at a rate of 1.7 μg m^{-3} per year, with trough times occurring between 06:00 and 07:00. Notably, the trough time shifted to 06:00 from 2017 to 2023 (excluding 2021).

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A notable observation was that ozone concentrations decreased during the day and increased at night. The annual variation curves of hourly ozone concentrations (Fig. 8c) indicated a significant declining trend during the high-value period from 13:00 to 15:00 (R = -0.54 to -0.80), with the most substantial average decrease occurring at 16:00, averaging 3.7 μg m^{-3} per year. This trend remained consistent, except for some anomalous values recorded in 2021. Conversely, an increasing trend in ozone concentrations was observed during other periods, particularly during the low-value period from 22:00 to 09:00 (R = 0.78 to 0.94), with an average increase at 08:00 of 2.2 μg m^{-3} per year. This trend indicates a reduction in the difference between peak and trough ozone values throughout the day, decreasing from 150 μg m^{-3} in 2013 to 104 μg m^{-3} in 2023, averaging a decline of 5.30 μg m^{-3} per year. The diurnal variation of ozone appears to be diminishing, suggesting a weakening of both daytime ozone generation and nighttime consumption.

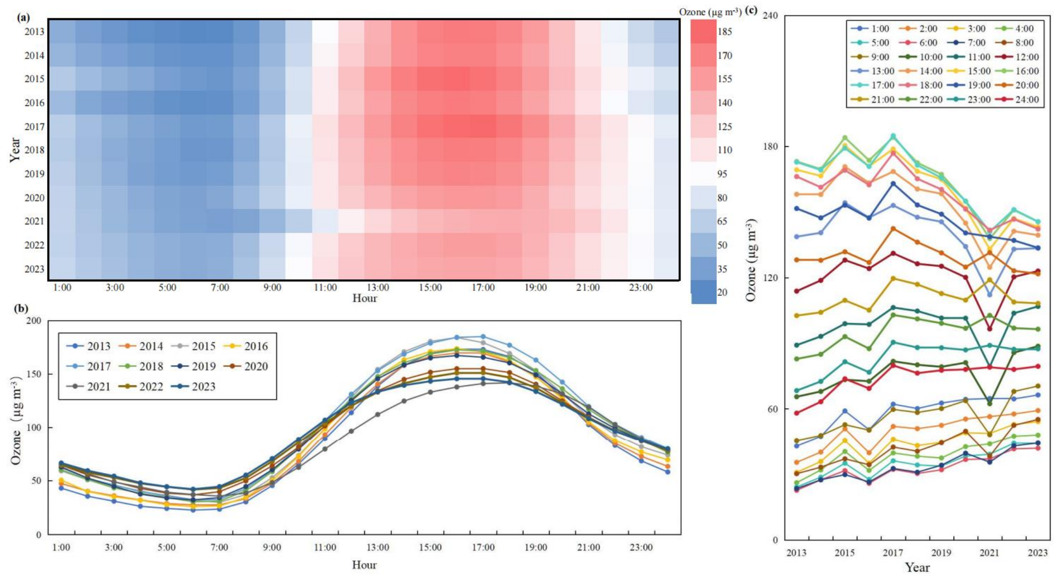

Figure 8 The diurnal variation of ozone in Beijing during the Ozone Season from 2013 to 2023 (a. an hourly color chart, b. a diurnal variation curve chart, c. a yearly variation chart of hourly concentration)

Similar phenomena have been observed in the United States during the summer(He et al., 2020), where increases in morning and evening ozone concentrations are linked to reductions in anthropogenic NOx emissions, which affect ozone titration. Chen(Chen et al., 2020) also noted a decrease in diurnal ozone variation amplitude in Beijing in recent years, particularly in lower concentration ranges. This study posits that significant reductions in NOx emissions over the years have led to decreased nighttime NO concentrations, weakening ozone consumption at night and contributing to increased nighttime ozone concentrations. Conversely, the decline in daytime ozone peaks is likely associated with coordinated reductions in volatile organic compound (VOC) emissions in Beijing(Kang et al., 2021; Zhan et al., 2021; Wang et al., 2022). Since 2017, stricter VOC emission controls have been implemented in Beijing and surrounding cities, leading to a continuous decrease in VOC concentrations(Wang et al., 2022). This decrease inhibits ozone

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generation during the day and contributes to the observed trend of lower concentrations in valuable daytime ranges.

3.5 Variation of ozone generation and consumption rates during Ozone Season in Beijing

By calculating the difference in ozone concentration between consecutive hours, we derived the hourly change rate of ozone ($V_i = P_i - P_{i-1}$), expressed in µg m^{-3} per hour. A positive V_i indicates a net generation of ozone, while a negative V_i reflects a net consumption state. A value of zero signifies a balance between generation and consumption. We plotted heat maps and curves of V_i for each year (Fig. 9a, 9b). The absolute value of V_i was lowest at 07:00, suggesting that, on average, the increase in ozone concentration begins around this time. The primary net generation of ozone occurred between 07:00 and 16:00, after which V_i became negative post-17:00, indicating the onset of net consumption. This led to a decline in ozone concentration until approximately 06:00 the following day.

Over the years, the maximum generation rate of ozone has exhibited a decreasing trend, accompanied by an advancement in the timing of its occurrence. In contrast, the maximum consumption rate has diminished without significant changes in its timing. The maximum value of V_i (V_{max}), which represents the peak generation rate, occurred during the hour before and after the most rapid generation period. Prior to 2016, the peak generation rate was concentrated between 11:00 and 13:00; however, post-2016, it gradually shifted earlier to between 10:00 and 12:00, indicating an advancement in peak generation time. From 2013 to 2015, V_{max} increased slightly from 24.7 µg m^{-3} per hour to 29.1 µg m^{-3} per hour, but subsequently declined to 18.2 µg m^{-3} per hour in 2023 (Fig. 9c). This reflects a decreasing trend in maximum ozone generation rates after 2015, at a rate of 1.0 µg m^{-3} per year.

The minimum value of V_i (V_{min}) indicates the maximum consumption rate, which ranged from -25.5 µg m^{-3} per hour to -13.5 µg m^{-3} per hour and was relatively low compared to the maximum generation rate. V_{min} typically occurred between 20:00 and 22:00, with 9 out of 11 years recording occurrences at 21:00. Over the years, a clear upward trend in V_{min} was observed, increasing at a rate of 1.2 µg m^{-3} per hour per year, suggesting a weakening of nighttime ozone consumption.

On average, ozone generation rates have exhibited a downward trend, resulting in smoother diurnal variations. The interval between the transition points of positive to negative V_i in the morning and evening represents the duration of ozone generation (T), which averaged 9 to 11 hours, with the shortest duration of 9 hours recorded in 2015. By subtracting the trough value from the peak value and dividing by the generation duration (T), we calculated the average generation speed ($V_{p=}(V_{max}-V_{min})/T$) of ozone. Over the years, V_p ranged from 9.4 to 17.1 µg m^{-3} per hour, demonstrating a decreasing trend at a rate of 0.69 µg m^{-3} per hour per year. This indicates that both the maximum generation and consumption rates of ozone in Beijing have slowed, with the rate of change in consumption exceeding that of generation, resulting in a reduced amplitude of diurnal variations.

The observed changes in ozone generation and consumption rates support the earlier conclusions about diurnal variation. This indicates that the amplitude of diurnal ozone variation is diminishing, along with a weakening in both ozone generation and consumption rates. Over the years, reductions in exhaust emissions have changed the characteristics of ozone-related photochemical reactions. Specifically, coordinated decreases in volatile organic compounds

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(VOCs) and nitrogen oxides (NOx) have led to lower diurnal average ozone generation rates. Additionally, the reduction in nighttime nitrogen oxides (NO) concentrations has diminished the titration effect on ozone during the night.

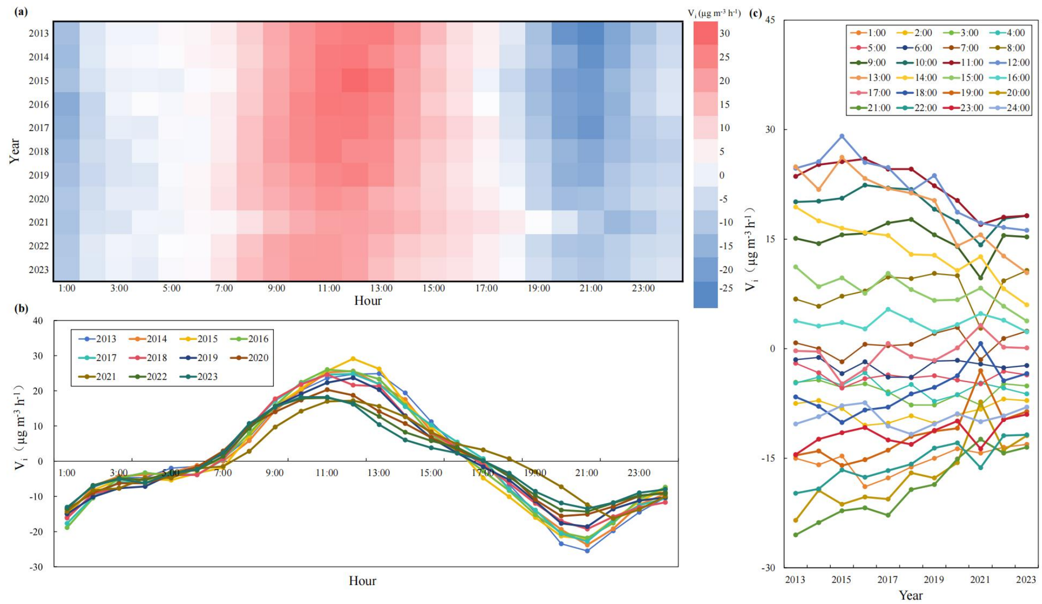

Figure 9 Daily rate of ozone change in Beijing during the Ozone Season from 2013 to 2023 (a. an hourly color chart, b. a diurnal variation curve chart, c. a yearly variation chart of hourly concentration)

3.6 Differences of diurnal variation between pollution days and Ozone Season in Beijing

To further investigate the variation in ozone pollution in Beijing over the years, we conducted an analysis of pollution days (MDA8 > 160 μg m^{-3}) for each year (see Table 2). From 2013 to 2023, the number of pollution days ranged from 24 to 74, demonstrating significant annual variability. More pollution days were observed from 2014 to 2019, peaking in 2019, followed by a substantial decline since 2020. The length of the Ozone Season varied from 115 to 181 days. There is a weak correlation between the length of the Ozone Season and the number of pollution days, and a longer Ozone Season may be accompanied by more pollution days.

The peak and trough values on pollution days exhibited trends similar to those observed during the Ozone Season, characterized by lower peaks and elevated troughs. A comparison of diurnal variations between pollution days and the Ozone Season revealed that the timing of peaks and troughs aligned, with peaks primarily occurring around 16:00 and troughs between 06:00 and 07:00. On pollution days, there was a discernible trend of decreasing peak values and increasing trough values, with peak decline rates of 2.5 μg m^{-3} per year, which is 30.9% lower than the peak reduction rate during the Ozone Season. In contrast, the trough increase rate of 2.4 μg m^{-3} per year was 37.3% higher than the corresponding rate during the Ozone Season.

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The similarity in diurnal variation patterns suggests that both ozone pollution days and typical days in Beijing are characterized by diminishing generation and consumption capabilities of ozone. The slower decline rate of peaks and faster increase rate of troughs on pollution days imply that favorable meteorological conditions lead to higher concentrations of precursors and NO in the atmosphere during these days, thereby enhancing ozone generation capacity, while nighttime conditions facilitate greater consumption.

Over the years, the concentration differences between pollution days and the Ozone Season have widened, with the ozone generation capabilities on pollution days remaining robust compared to those during the Ozone Season. Fig. 10 presents a heat map illustrating the concentration differences between pollution days and the Ozone Season. Hourly ozone concentrations on pollution days consistently exceeded those in the Ozone Season, with peak values surpassing 43 to 57 μg m^{-3}. In contrast, the differences in trough values were not significantly pronounced, ranging from 1 to 11 μg m^{-3}.

Notably, the hourly concentration differences between pollution days and the Ozone Season have shown an increasing trend over the years, with peak differences averaging an increase of 0.97 μg m^{-3} per year and trough differences increasing by 0.65 μg m^{-3} per year. The correlation coefficients for these trends were 0.65 and 0.68, respectively. Additionally, nighttime concentration differences have become considerably more pronounced, rising from 19.2 to 34.2 μg m^{-3}, with an increase rate of 1.33 μg m^{-3} per year.

The increase in hourly concentration differences between pollution days and the Ozone Season suggests that while overall ozone generation capabilities are declining, the rate of reduction on pollution days is comparatively slower. This means that these pollution days still have a significant capacity for ozone generation.

Table 2 Ozone pollution days and Ozone Season in Beijing from 2013 to 2023

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Ozone pollution days	53	73	69	69	60	67	74	54	24	52	53
Ozone Season	129	165	164	147	134	166	170	163	115	175	181

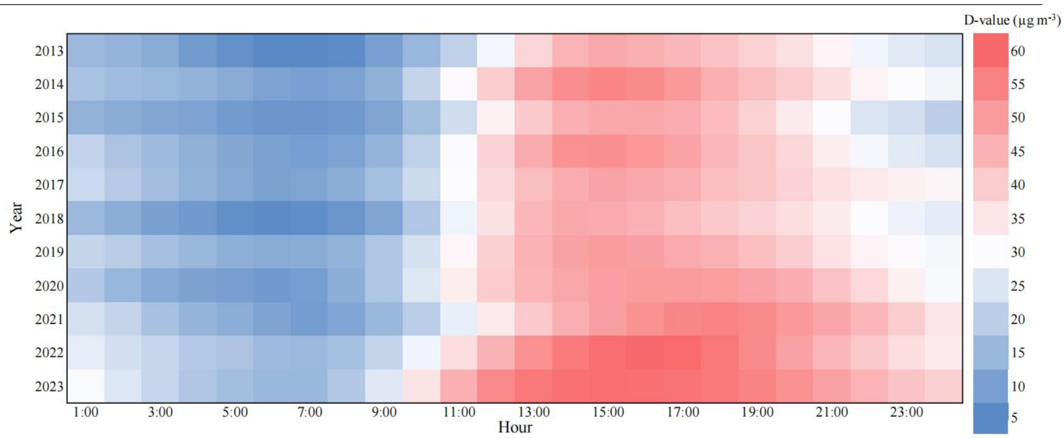

Figure 10 Differences in diurnal variation between pollution days and Ozone Season in Beijing from 2013 to 2023

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4. Conclusions

Beijing's stringent air pollution control measures over the years have significantly improved air quality; however, the variation in ozone concentration in Beijing is not as pronounced as that of PM2.5. This article studied the evolution of ozone in Beijing from 2013 to 2023. Firstly, we defined the concept of the Ozone Season, considering the period in which the maximum daily average of 8-hour ozone (MDA8) exceeds 160 μg m^{-3} as the urban Ozone Season. The study found that over the years, the start of the Ozone Season in Beijing has advanced, while the end has been postponed, resulting in an average extension of 2.01 days per year. Secondly, the analysis indicates that the low percentile ozone concentrations in Beijing have increased, which may be related to a decline in regional NOx emissions, consistent with other international research findings(Chen et al., 2020; Sicard, 2021; Niu et al., 2022); however, changes in high percentile concentrations are not significant. Thirdly, the duration of ozone exposure, represented by the duration of ozone MDA8, has been increasing in both the cold and warm seasons, with a more notable extension in the cold season. In the warm season, ozone exposure can persist into the nighttime, highlighting the importance of monitoring the potential health effects of nighttime ozone levels. Finally, regarding the diurnal variation pattern, over the years, the typical peak ozone concentrations during the ozone season in Beijing have decreased, while the valley concentrations have increased, leading to a more gradual diurnal variation. International studies suggest that the increase in nighttime ozone concentrations is associated with reducing NOx levels, resulting in weaker NO titration(He et al., 2020; Chen et al., 2020). The decrease in peak concentrations benefits from coordinated emission reduction policies for regional VOCs and NOx(Wang et al., 2022). In correspondence with the annual changes in peak and valley values, the ozone generation rate and consumption rate during the ozone season in Beijing has declined, indicating a decrease in both generation and consumption capacity. The variation pattern of peak and valley values on days with exceeded ozone levels is consistent with the Ozone Season; however, the rate of decline for peak values is slower, while the rate of increase for valley values is faster, indicating that exceeded days still have a strong ozone generation capacity.

The conclusions of this study indicate that the baseline ozone concentration in Beijing has been rising over the years, the timing of ozone pollution events is advancing, and the city is experiencing a longer Ozone Season, consequently extending the potential impact period on human health. While trough values are rising, peak values are declining, ozone generation speeds are decreasing, the start time for generation is advancing, and consumption speeds are also dwindling, leading to a smoothing of diurnal variations. In recent years, there has been a significant reduction in NOx concentrations in Beijing, with NO_2 levels decreasing by 53.7% in 2023 compared to 2013(Beijing Municipal Bureau of Ecology and Environment, 2024), resulting in weakened nighttime titration effects of NO on ozone and an increasing trend in trough and nighttime ozone concentrations. The reduction in peak concentrations may be attributed to stringent VOC controls, with coordinated reductions in VOCs and NOx leading to diminished ozone generation ability during the day. With the decrease in precursor emissions, significant changes in ozone generation control zones across various regions and months in Beijing have also been observed. The trends in ozone variation are influenced not only by changes in pollution emissions, but also by climatic factors. Further comprehensive analyses are needed to explore the causes, which will require the use of chemical models and experiments for simulation verification to assess the relative contributions of emissions and climate changes.

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Data availability

Hourly surface ozone observations are provided by the China National Environmental Monitoring Centre (CNEMC) and are available at:https://www.cnemc.cn/en/(last access: 6 February 2025).

Author contribution

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Xiaofei Dong: Conceptualization, Software, Writing-Reviewing and Editing
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Xiue Shen: Conceptualization, Supervision, Editing, Project administration
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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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