The effects of meteorological factors on ozone during summer in Shanghai, China

Shengyang Duan¹, Chenhang Zhao¹, Yonghang Chen¹ and Qiong Liu¹,²

¹Environmental Science and Engineering College, Donghua University, Shanghai, China
²Corresponding author’s e-mail: liuqiong@dhu.edu.cn

Abstract. Based on the surface observation data from 2011 to 2013, the effects of meteorological factors on ozone are revealed during summer in Shanghai by analyzing the visibility, temperature, and relative humidity. When ozone pollution occurred, visibility and relative humidity decreased significantly, 10%–30% and 15%–35%, respectively. The ozone concentration was negatively correlated with visibility and relative humidity. While the higher the temperature is, the more conducive to the photochemical formation of ozone. Ozone pollution in Shanghai mainly occurred in meteorological conditions with visibility from 6–8 km, temperature from 25 ℃–35 °C, and relative humidity from 20%–50%. The temperature made a more outstanding contribution to ozone generation when ozone concentrations were much higher than 200 µg/m³.

1. Introduction

In recent years, ozone has become the primary pollutant affecting air quality during summer in megacities in China [1,2]. Pairidiguli et al. [3] found that the concentrations of PM2.5 and ozone in the Yangtze River Delta were decreasing and increasing, respectively. Yi et al. [4] found that the most severe ozone pollution in the Yangtze River Delta usually occurred from May to August using the data from China National Environmental Monitoring Centre. Precursors and meteorological factors significantly impact urban summer ozone concentration [5,6]. Using the Weather Research and Forecasting Model-Community Multi-scale Air Quality Model(WRF-CMAQ), Yan et al. [7] found that volatile organic compounds (VOCs) mainly controlled ozone concentrations in Shanghai.

In addition to precursors, meteorological factors also have significant effects on ozone formation. Temperature and relative humidity are two crucial meteorological factors affecting the formation of near-ground ozone [8,9]. Yan et al. [10] analyzed the meteorological data of Jiangsu Province from 2013 to 2017, and the results showed that the ozone mass concentration in Jiangsu Province was generally positively correlated with temperature and negatively correlated with relative humidity. The temperature is higher than 25 ℃, the relative humidity is 30%–50%, or the wind speed below 4 m·s⁻¹ is prone to ozone pollution [9]. Cui et al. [11] studied the factors affecting the rapid growth of near-surface ozone concentration in the Beijing-Tianjin-Tangshan region in 2016 and found that the influence of temperature was positively correlated. The most obvious was a specific negative correlation with pressure and a slight positive correlation with evaporation. Wang et al. [12] found that ozone and the daily visibility change showed a significant positive correlation based on the 2013 Shenyang ozone and meteorological data. When particles, especially the secondary fine particulate matter, increase in the air, visibility becomes lower, which can change solar radiation and thus affect ozone concentration [13].
The main task of air pollution control in China is to control ozone and fine particulate matter concentrations simultaneously. According to the previous studies [14-16] in China, haze is caused by fine particulate matter in the air, when the visibility is less than 10 km, and the relative humidity is less than 95% without any precipitation, dust storm, blowing sands, floating dust, smokes, blowing snows, or snowstorms. The visibility is an essential indicator of air quality and can better reflect the cleanliness of the ground atmosphere [17]. Therefore, visibility can be used as a meteorological parameter reflecting particle concentrations in the atmosphere. In addition to particulate matter, other meteorological factors also affect visibility, with relative humidity having the most significant impact [18-23]. In Shanghai, visibility is mainly affected by PM10, which correlates with temperature and relative humidity [24].

Visibility is a critical meteorological parameter, which can reflect the particulate matter concentrations and affect the formation of near-surface ozone [25]. Therefore, the primary goal is to further understand the influence of meteorological factors on near-surface ozone concentrations by considering visibility in Shanghai.

2. Methods

2.1. Observation site
The Shanghai Meteorological Bureau began to build an atmospheric composition observation network in 2005. The data (2011-2013) were from six stations representing different functional zones (Figure 1) to analyze the impact of different meteorological factors on ozone concentrations. Xuhui is a large commercial, residential zone in the southwest of central Shanghai, not far from the Shanghai Min Viaduct and inner ring viaduct, one of the important urban transportation hubs. Pudong is a large green space, office, and residential zone. Baoshan and Jinshan are steeling industrial zone and petrochemical zone, respectively. Chongming is an ecological island area with a high green coverage rate. Dongtan is a large wetland nature reserve, far away from the urban area and less affected by human activities, representing Shanghai’s atmospheric background value of atmospheric pollutants.

![Figure 1. The geographical location of the observation stations.](image)

2.2. Surface observation data
In this paper, the ozone concentrations were obtained from the ML9810B ozone analyzer. When the hourly ozone concentration is higher than 200 µg/m³, ozone concentration exceeded the standard, and ozone pollution occurred. The meteorological data such as temperature, atmospheric pressure, relative humidity, wind speed, wind direction, visibility, precipitation, etc., are all from the Milos500 seven-element automatic weather station.

2.3. Data processing method
Table 1 shows the statistical data of the hourly average ozone concentrations of the six stations. The lack of data is mainly caused by instrument maintenance, zero range calibration, or data quality control.
Ozone analysis and evaluation mainly use hourly average concentration without precipitation. Since ozone is a product of photochemical reactions, ozone pollution is mostly concentrated in summer and daytime. Thus, the data from May to August and 6 o'clock to 20 o'clock from 2011 to 2013 were used in this paper. The hourly data are divided into two situations: exceeding the standard (ozone concentration higher than 200 µg/m³) and meeting the standard (ozone concentration less than 200 µg/m³).

Table 1. Statistics on the characteristics of hourly average concentrations of ozone at six stations in Shanghai.

| Station   | The total number of valid samples | Data integrity rate | Max (µg/m³) | Mean (µg/m³) | Median (µg/m³) | Standard deviation (µg/m³) |
|-----------|----------------------------------|--------------------|-------------|--------------|----------------|-----------------------------|
| Baoshan   | 24576                            | 93.43%             | 327         | 52           | 46             | 39                          |
| Chongming | 24188                            | 91.96%             | 357         | 70           | 66             | 42                          |
| Dongtan   | 24115                            | 91.68%             | 344         | 84           | 82             | 39                          |
| Jinshan   | 24488                            | 93.10%             | 418         | 74           | 66             | 52                          |
| Putong    | 24466                            | 93.01%             | 353         | 61           | 55             | 43                          |
| Xujiahui  | 24663                            | 93.76%             | 291         | 42           | 36             | 34                          |

3. Results and discussion

3.1. The relationship between ozone and visibility

Figure 2 shows the visibility comparison when the ozone concentrations exceeded or not exceeded 200 µg/m³ in Shanghai. The visibility of almost all sites decreases when the ozone concentration exceeds the standard. In all the stations, the difference between Baoshan and Jinshan in the industrial park is more prominent, decreasing by 23.84 % and 26.16 %. Moreover, the other stations are not prominent. The reason is that Baoshan and Jinshan are industrial areas, and their PM10 concentration is relatively high, which causes a significant change in visibility.

Figure 3 shows the daily changes in visibility when ozone concentrations meet and exceed the standard in Shanghai. Unlike Figure 2, when the ozone concentration meets the standard, the visibility of each site has a very consistent diurnal variation, showing a single-peak and single-valley structure. Zhou et al. [26] showed that the diurnal variation of visibility in Shanghai in winter is a single-peak feature. The valley appears at about 5 o'clock, the peak appears at about 14 o'clock, and the changes are relatively smooth. When the ozone concentration exceeds the standard, the visibility is generally lower. The visibility trend of Jinshan station from 8 o'clock to 23 o'clock is the same as that when the ozone concentration meets the standard. There is a peak at 16 o'clock, and the visibility at each time is, on average 3 km-4 km lower than when the ozone concentration was less than 200 µg/m³.
At Dongtan station, except for the time when the fluctuation is significant, the trend from 11 o'clock to 19 o'clock is more similar to that when there was no ozone pollution; Baoshan station is an industrial park site when the ozone concentration exceeds the standard, the average level of visibility is higher than Pudong and Jinshan. However, the visibility of the three stations varies greatly, and the overall decrease is between 28% and 33%, indicating the daily change. The ozone concentration in Shanghai is negatively correlated with visibility, consistent with the study of Wang et al. [27]. When the fluctuation is significant, high ozone concentrations are mostly concentrated at 12:00 – 16:00, and the fluctuation of ozone concentration is slight. At other times, the corresponding visibility samples are also small due to the small number of samples when ozone concentration exceeds the standard, and there will be large fluctuations [28]. For example, the ozone concentrations exceeding the standard at Xujiahui and Baoshan stations at 13:00 were the highest, only accounting for 23.68 % and 20.65 %, respectively [29].

The summer visibility in Shanghai has the most remarkable correlation with PM$_{10}$ [30]. The greater the concentration of PM$_{10}$, the lower the visibility. Many studies have found that PM$_{10}$ and ozone concentrations show opposite trends, Zhao et al. [29], Shao et al. [31], and other studies have found that ozone and PM$_{10}$ in Shanghai are opposite. It may be that the atmosphere is highly oxidative in summer, and secondary particles are generated at the same time as O$_3$, which leads to a positive correlation between PM$_{10}$ and O$_3$ concentrations, which in turn causes a negative correlation between ozone concentration and visibility. In general, urban areas are more prone to strong updrafts in the afternoon of summer, a significant driving force for severe convective weather. The short-time heavy precipitation in the afternoon is essential for the wet deposition of aerosols [32], improving visibility. It may be one of the reasons for the peak visibility at 17:00 when the ozone concentrations in Xujiahui exceeded the standard.

![Figure 3. Comparison of daily changes in average visibility when ozone concentrations meet and exceed the standard in Shanghai (a: Baoshan; b: Jinshan; c: Dongtan; d: Pudong; e: Chongming; f: Xujiahui).](image)

3.2. The influence of temperature
As shown in Figure 4, the temperature significantly changes when the ozone reaches the standard and exceeds the standard. When the ozone concentrations were less than 200 µg/m$^3$, the temperature was about 25 °C. When ozone pollution occurs, temperatures at all six sites exceed 30 °C, with Baoshan and Xujiahui reaching 34 °C and 35 °C. The temperature when the ozone concentration exceeds the standard is generally higher than when the ozone reaches the standard.
Figure 4. Comparison of average temperature when ozone concentrations meet and exceed the standard in Shanghai.

Figure 5 further analyzes the daily average temperature changes under different ozone concentrations in detail. When the ozone reached the standard, the daily temperature changes at all sites were relatively consistent, peaking around 14:00. Except for the generally low temperature in Dongtan, the daily temperature changes at other sites were between 24 °C and 30 °C. When the ozone concentration exceeds the standard, the daily temperature changes at each station are different, and there is no certain regularity. The temperature range of each station is 33 °C to 37 °C at Baoshan station, 30 °C to 36 °C at Pudong station, 28 °C to 34 °C at Dongtan station and 27 °C to 31 °C at Jinshan station. As a wetland at the mouth of the Yangtze River, Dongtan has a low base temperature. When the ozone concentration exceeds the standard at Jinshan station, the temperature is significantly lower, especially in the high-temperature area than in other stations. Jinshan is an area with severe ozone pollution, making it many high ozone concentration situations during non-high temperature periods. Compared with other areas, Jinshan is an industrial area, producing more VOCs (ozone precursors), which is more conducive to the photochemical formation of ozone. Therefore, when ozone pollution occurs in Jinshan station, the temperature is lower than in other stations.

Figure 5. Comparison of daily average temperature changes when ozone concentrations meet and exceed the standard in Shanghai (a: Baoshan; b: Jinshan; c: Dongtan; d: Pudong; e: Chongming; f: Xujiahui).

3.3. The influence of relative humidity

Figure 6 shows that the relative humidity changes significantly when the ozone concentration reaches the standard and exceeds the standard. Relative humidity in the six stations when ozone concentration exceeds standard is lower than when ozone concentration meets standard. Specifically, the percentages
of relative humidity reduction at the time when ozone concentration exceeds the standard are 40.00%, 38.75%, 30.49%, 25.32%, 38.67%, and 47.83% in Baoshan, Chongming, Dongtan, Jinshan, Pudong, and Xujiahui, respectively.

Figure 6. Comparison of the average relative humidity when ozone concentrations meet and exceed the standard in Shanghai.

Figure 7 shows the specific changes in relative humidity when ozone reaches the standard and exceeds the standard. When the ozone reaches the standard, the daily change of humidity is relatively regular, opposite to the daily change of temperature, and the difference between each site is not significant. It is a valley around noon, and the relative humidity is basically between 60% and 70%. When the ozone concentration exceeds the standard, the relative humidity of each station has a significant decrease, and its trend is similar to the daily change of the relative humidity when the ozone reaches the standard, and the decrease ratio is about 15%-35%. The results are consistent with Cui et al. [33], Chen et al. [34], and Li et al. [35]. The "wet scavenging" effect of high relative humidity on O$_3$ is mainly related to the activity of OH in the atmosphere. OH· is an essential oxidant in the tropospheric atmosphere. According to the photochemical reaction mechanism [36], the reaction between VOCs and OH to form peroxyalkyl groups is a fast-paced step in the chain photochemical reaction process [37]. Because OH· will affect the photochemical process of O$_3$ production, it is not conducive to the accumulation of O$_3$.

Figure 7. Comparison of daily changes in average relative humidity when ozone concentrations meet and exceed in Shanghai (a: Baoshan; b: Jinshan; c: Dongtan; d: Pudong; e: Chongming; f: Xujiahui).
3.4. The joint influences of temperature, relative humidity, and visibility on ozone

Figure 8 shows that the visibility is mainly 6 km-9 km when the ozone concentrations exceed the standard. When the visibility is 6 km-9 km, the temperature is 25 °C-36 °C, and the relative humidity is 25 %-60 % (Figure 9). As the ozone concentration increases, the relative humidity gradually decreases, and the temperature slowly rises. When the visibility exceeds 9 km, the ozone concentration exceeded the standard decreases gradually, especially in the situation of ozone concentration exceeds 225 µg/m³. The temperature is positively correlated with visibility. When the visibility is less than 6 km, ozone pollution occurs less. The relative humidity is high, from 45 % to 70 %, and the temperature is low. Ozone pollution in Shanghai often occurs under low visibility, high temperature, and low relative humidity [38]. With the decrease of visibility, the temperature is lower, and the relative humidity is higher when ozone pollution occurs. When the visibility is in the range of 6 km-8 km, the temperature is about 30 °C, the relative humidity is 20 % -30 %, ozone concentration is more likely to exceed 250 µg/m³, and more severe ozone pollution events may occur.

![Figure 8](image)

**Figure 8.** The ratio of samples with different visibility when ozone concentrations exceed the standard during May-August of 2011-2012 at Pudong station.

![Figure 9](image)

**Figure 9.** Bubble graphs of temperature and relative humidity under different visibility when ozone concentrations exceed the standard during May-August of 2011-2012 at Pudong station.

### 4. Conclusion

1. The ozone concentration was negatively correlated with visibility. When ozone pollution occurs in Shanghai, the visibility of six stations generally decreased. Among them, the visibility in Baoshan, Pudong, and Jinshan decreased most, with an overall decline of 28% to 33%.

2. When ozone pollution occurs, the temperature range of each site is 27 °C to 37 °C, indicating that the higher the temperature is, the more conducive to the photochemical formation of ozone. When there was no ozone pollution, the diurnal variation trend of temperature in the six stations was consistent, and
the peak temperature appeared at about 14: 00. The temperature of the other stations was between 24 °C and 30 °C, except that the temperature of Dongtan was generally low.

(3) When the ozone concentrations were less than 200 µg/m³, the diurnal variation of relative humidity reached the minimum at 12: 00, which was basically between 60 % and 70 %. When the ozone concentrations were higher than 200 µg/m³, the relative humidity of all stations had a significant decline, and the decline rate was about 15%-35%, indicating that the lower the relative humidity, the higher the ozone concentration.

(4) Ozone pollution mainly occurred in meteorological conditions with visibility from 6 km-9 km, temperature from 25 °C-36 °C, and relative humidity from 25%-60%. The temperature made a more outstanding contribution to ozone generation when ozone concentrations were much higher than 200 µg/m³.

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