The Modulation of Meteorological Parameters on Surface PM_{2.5} and O₃ Concentrations in Guangzhou, China

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ABSTRACT

PM_{2.5} and ozone (O₃) are two major pollutants that are worsening air quality in China. Using Guangzhou as a case study, we analyzed the meteorological data and air quality data for 2014–2016 obtained by 4 weather stations and 10 environmental monitoring stations, respectively, and assessed the influence of significant meteorological parameters on the hourly PM_{2.5} concentration and the daily maximum 8-hour-averaged (MDA8) O₃ concentration. Calculating each factor's critical values for these concentrations, we found that the hourly PM_{2.5} concentration tended to increase when the relative humidity was > 50%, the hourly rainfall intensity was ≤ 0.6 mm hour⁻¹, or the wind speed was ≤ 1.8 m s⁻¹ but otherwise decreased, whereas the MDA8 O₃ concentration tended to increase when the sunshine duration was > 4 hours, the maximum temperature was > 29°C, or the average daily wind speed was ≤ 1.8 m s⁻¹ but otherwise decreased. The wind direction was also a crucial factor, as Guangzhou typically experienced severe air pollution when westerlies prevailed. Applying the critical values of these various meteorological parameters as indicators of air quality, we discovered that the least favorable weather conditions during the study period occurred in 2014. These results further our understanding of the relationship between weather conditions and pollutant concentrations. Following the novel approach proposed in this study, meteorological parameters can be utilized to forecast the air quality or compare the effects of weather on pollution between different years.

Keywords: Meteorological parameters, Critical value, PM_{2.5}, Ozone, Guangzhou

1 INTRODUCTION

Severe PM_{2.5} (particulate matter with an aerodynamic diameter < 2.5 μm) and ozone (O₃) pollutions in China have attracted the attention of both scientific community and policy makers (Pope and Dockery, 2013; Huang *et al.*, 2014; Wang *et al.*, 2017). Elevated PM_{2.5} concentration can reduce the atmospheric visibility, damage the human respiratory system, and affect the radiative forcing and regional weather climate (Charlson *et al.*, 1992; Pui *et al.*, 2014; Deng *et al.*, 2016), while high surface O₃ concentrations are harmful to human health and terrestrial vegetation (Fuhrer *et al.*, 1997; West *et al.*, 2006). Various emission control measures have been implemented by the Chinese government to improve the air quality since 2013, leading to a decrease in PM_{2.5} concentration (Zhang *et al.*, 2019) but an increase in ozone concentration (Li *et al.*, 2019). Overall, PM_{2.5} and O₃ are still the major pollutants and the concentrations of them

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frequently exceed the national air quality standard. Besides emissions, meteorological conditions play an important but varying role in the changes in pollutant concentrations (Liu and Wang, 2020). The meteorological parameters are decisive to the temporal and spatial distribution of pollutant concentrations within a short-term period (Zhang *et al.*, 2013a; Zhang *et al.*, 2015; Cai *et al.*, 2017). Hence, a further understanding of the relationships between meteorological parameters and pollutant concentrations is of significance.

The influence of meteorological conditions on air quality is generally analyzed from the aspects of weather classification (Russo *et al.*, 2014; Zhang *et al.*, 2016), diffusion conditions (Pasch *et al.*, 2011; Wu *et al.*, 2013), and surface meteorological parameters (Khedairia and Khadir, 2012). The method of weather classification can only give a qualitative correspondence for local air quality due to its large spatial scale (Zhang *et al.*, 2013b; Russo *et al.*, 2014). Atmospheric diffusion conditions are usually characterized by ventilation coefficients, in which the boundary layer height is usually observed by sounding or Lidar, or acquired by reanalysis data. However, the observational sites are relatively sparse, and either observed or modeled boundary layer height has a large uncertainty. Thus, the analysis of surface meteorological measurement is still the most effective way to quantitatively describe the impact of meteorological conditions on local air quality owing to its dense observation sites and long-term sequence (Zhang *et al.*, 2015).

Previous studies have used surface meteorological observations to investigate the impact of various meteorological parameters on the concentrations of PM_{2.5} and O₃. Zhang *et al.* (2015) used the correlation method to analyze the relationships between meteorological parameters, and surface O₃ and PM_{2.5} concentrations in Beijing. Their results showed that the average wind speed and relative humidity were the most closely correlated with O₃, whereas relative humidity and sunshine hours were the most closely correlated with PM_{2.5} in winter, followed by spring, autumn, and summer. They also found that sunshine duration, the mean wind speed, and the wind direction were closely related to the O₃ concentration. Wang and Ogawa (2015) used the correlation and linear regression methods to reveal the effect of meteorological conditions on PM_{2.5} concentration in Nagasaki, Japan. They demonstrated that PM_{2.5} concentration was negatively correlated with the temperature, and positively correlated with the precipitation. Its concentration had a positive or negative relationship with the humidity and wind speed, depending on the values of meteorological parameters. For the wind direction, the westerly wind may bring more pollutants to Nagasaki. Given the accumulative and cleaning effects of wind speed on PM_{2.5} concentration, Tie *et al.* (2015) proposed the concept of “balanced wind” by a box model to estimate the critical value of wind speed that balanced the continuous emissions and atmospheric cleaning processes. Namely, when the wind speed is lower than the balanced wind, the local air quality is under an accumulative mode, which is favorable to the increase in pollutant concentrations. Otherwise, it is in a cleaning mode, which tends to decrease the pollutant concentration. Based on this concept, Xu *et al.* (2016) directly used the measurements of the wind speeds and the PM_{2.5} concentrations to calculate the balanced wind speed in Shanghai. They showed that the balanced wind speed (1.8 m s⁻¹) was the key indicator affecting the local accumulation and dispersion of PM_{2.5}.

Despite these studies, a comprehensive study on the modulation by various meteorological parameters of PM_{2.5} and O₃ concentrations in a local area is still demanded. Most previous studies revealed the relationships between meteorological parameters and pollutant concentrations by calculating the correlation coefficients of them but not by quantitatively assessing the critical values of different meteorological parameters. Besides wind speed, other meteorological parameters, including temperature, relative humidity, precipitation, and sunshine duration, also have critical values for the variability of pollutant concentrations, which need to be calculated comprehensively. These critical values could be considered as the meteorological indicators of the changes in pollutant concentrations and guide air quality forecast.

The Pearl River Delta (PRD) region is one of the three major economic zones in China, located in the south coast of mainland China. With the rapid development of urbanization and industrialization, the atmospheric pollution problem caused by fine particles and ozone pollution has been highlighted (Zhang *et al.*, 2008; Fang *et al.*, 2019; Wu *et al.*, 2019). Taking Guangzhou (see Fig. 1 for its location), the typical megacity in PRD, as an example, this study aims to investigate the variation of meteorological parameters on PM_{2.5} and O₃ concentrations using the meteorological and air quality observations. Critical values of these meteorological parameters

Fig. 1. Locations of weather stations (*) and environmental monitoring stations (•) used for analysis in Guangzhou.

for the variability of $\text{PM}_{2.5}$ and O_3 concentrations were calculated. We also used these critical values to evaluate the favorability of meteorological conditions during 2014–2016. Section 2 shows the data and method and Section 3 presents the analysis results. The conclusion and implication are given in Section 4.

2 DATA AND METHOD

2.1. Measurement Data

We obtained surface meteorological data from Guangdong Meteorological Administration and pollutant observation data from Guangdong Environmental Monitoring Center. The observed meteorological parameters consisted of temperature, relative humidity, wind speed and wind direction, precipitation, and sunshine duration from 2014 to 2016 at 4 weather stations in Guangzhou. Pollutant measurement data included the concentrations of $\text{PM}_{2.5}$ and O_3 during the same period at 10 environmental monitoring stations in Guangzhou. The measurements of meteorological parameters and pollutant concentrations were not conducted at the same sites and the locations of meteorological stations and environmental monitoring stations are shown in Fig. 1. We combined the observed pollutant concentrations at the environmental monitoring stations with the nearest weather station of meteorological parameters. If there are two or more environmental monitoring stations available, the data of these stations were averaged. Therefore, four datasets, namely those at Wushan, Luogang, Panyu, Huadu sites, were derived to investigate the relationships between meteorological parameters and pollutant concentrations. The data of these four sites were averaged to represent the overall conditions in Guangzhou.

2.2 Methods

Following the concept of “balanced wind speed” proposed by Tie *et al.* (2015), we investigated the critical values of meteorological parameters for the variability and change rate of $\text{PM}_{2.5}$ and O_3 concentration. The hourly variability of $\text{PM}_{2.5}$ was derived from the changes in the current hourly concentration relative to that of the previous hour, while the daily variability of daily maximum 8-hour-averaged (MDA8) O_3 was derived from the changes in the daily concentration relative to that of the previous day. The hourly change rate of $\text{PM}_{2.5}$ [(PM in the current hour – PM in the previous hour)/PM in the previous hour $\times 100$] and daily change rate of MDA8 O_3 [(O_3 in the day – O_3 in the previous day)/ O_3 in the previous day $\times 100$] were also derived. Since

the modulations of individual meteorological parameters for $\text{PM}_{2.5}$ and O_3 are different, we focused on the key meteorological parameters affecting the concentrations of them according to the previous studies. For $\text{PM}_{2.5}$ concentration, its relationships with the hourly relative humidity, rainfall intensity, wind speed, and wind direction were explored (Qian *et al.*, 2009; Sun *et al.*, 2013; Wang and Ogawa, 2015; Xu *et al.*, 2016). For MDA8 O_3 concentration, the modulations of sunshine duration, maximum daily temperature, wind speed, and wind direction on it were revealed (Toh *et al.*, 2013; Zhang *et al.*, 2015). In this study, the results for the Wushan, Luogang, Panyu, Huadu sites and four-site average in Guangzhou were analyzed.

3 RESULTS

3.1 Effects of Meteorological Parameters on $\text{PM}_{2.5}$ Concentration

3.1.1 Relative humidity

Relative humidity plays an important role in the chemical compositions, size distributions, and optical properties of aerosol (Sun *et al.*, 2013). The increase in relative humidity can increase the aerosol hygroscopicity, particle size, and thus affect atmospheric visibility (Tan *et al.*, 2013). Moreover, the droplets generated through the aerosol hygroscopic growth are conducive to the heterogeneous reactions on its surface (Sievering *et al.*, 1991), which can increase the $\text{PM}_{2.5}$ concentration. Fig. 2 shows the variability and change rate of $\text{PM}_{2.5}$ concentrations in different relative humidity sectors by an interval of 5%. The samples with precipitation were excluded. The change rate was most significant when the relative humidity is $\leq 20\%$. The $\text{PM}_{2.5}$ variability is positive if the relative humidity is $> 40\%$, $> 50\%$, $> 45\%$, and $> 40\%$ at Wushan, Luogang, Panyu, and Huadu sites, respectively. For overall Guangzhou, the critical value of relative humidity is 50%. The increase in $\text{PM}_{2.5}$ concentration with relative humidity $> \sim 50\%$ was attributed to the aerosol hygroscopicity growth. With the decrease in relative humidity from $\sim 50\%$, the $\text{PM}_{2.5}$ variability switches to be negative, which tends to decrease the concentration. In southern China, the low relative humidity often occurs when it is under the control of cold anticyclone weather system. During this period, the wind speed is high enough to be favorable for the diffusion of pollutants. Meanwhile, the fresh emitted and generated particles have small mean diameter with a weak hygroscopicity. Together with low relative humidity, the hygroscopic growth of aerosol is insignificant (Tan *et al.*, 2013, 2017). As a result, the low relative humidity is unfavorable for the increase in $\text{PM}_{2.5}$ concentrations.

3.1.2 Hourly rainfall intensity

Precipitation interacts actively with the particles in the air (Qian *et al.*, 2009). Fig. 3 depicts the $\text{PM}_{2.5}$ variability and change rate in different rainfall sectors by an interval of 0.1 mm hour^{-1} . The change rate was more significant in high rainfall intensity. The critical values of rainfall intensity at Wushan, Luogang, Panyu, and Huadu sites are 0.5, 0.7, 0.6, and 0.6 mm hour^{-1} , respectively. In Guangzhou, the $\text{PM}_{2.5}$ variability becomes positive when the rainfall intensity $\leq 0.6 \text{ mm hour}^{-1}$. The increase in $\text{PM}_{2.5}$ concentrations at low rainfall intensity can be explained by three reasons. First, when the rainfall intensity is small, the relative humidity in the air increases with the evaporation of the raindrops; hence the $\text{PM}_{2.5}$ concentration will increase due to aerosol hygroscopic growth (Tan *et al.*, 2017). Second, small raindrops can promote the heterogeneous reactions of gases on particle surfaces, where reaction products will remain, which increase the concentrations (Fan *et al.*, 2015). Third, the scavenging effect of small rain droplets on particles is inefficient (Zhang *et al.*, 2004). According to the civil aviation meteorological ground observation specification developed by the Air Traffic Management Office of Civil Aviation Administration of China (2020), the hourly rainfall is classified into light rain ($\leq 2.5 \text{ mm hour}^{-1}$), moderate rain ($2.6\text{--}8.0 \text{ mm hour}^{-1}$), and heavy rain ($\geq 8.1 \text{ mm hour}^{-1}$). The result shown that the light rain can not only scavenge pollutants but also promote the aerosol hygroscopic growth, and the cleaning effect of the moderate rain on particles is not as significant as that of the heavy rain. Fig. 3 also shows that the particle removal efficiency by rainfall is significantly effective when hourly rainfall intensity $\geq 8 \text{ mm hour}^{-1}$. We also found that the removal efficiency is relatively small when the hourly rainfall intensity ranging from 6 to 9 mm hour^{-1} . The particle concentration before precipitation

Fig. 2. Hourly mean change rate and variability of $PM_{2.5}$ concentrations in different relative humidity sectors during 2014–2016 for (a) Wushan, (b) Luogang, (c) Panyu, and (d) Huadu sites, and (e) four-site average.

could be the causes. If the concentration before precipitation is low, the scavenging effect will be insignificant.

3.1.3 Hourly wind speed

Xu *et al.* (2016) found that the horizontal wind speed is decisive to the influence of local diffusion capacity. Fig. 4 shows the $PM_{2.5}$ variability and change rate in different wind speed sectors by an interval of 0.2 m s^{-1} . There are 11,175 effective samples after eliminating those with precipitation. The change rate was more significant with low wind speed. In Guangzhou, the balanced wind speed was 1.8 m s^{-1} . Namely, when the wind speed $\leq 1.8 \text{ m s}^{-1}$, the $PM_{2.5}$ mass concentrations tended to increase according to the positive variability indicative of the accumulative mode. In contrast, when wind speed was $> 1.8 \text{ m s}^{-1}$, the $PM_{2.5}$ variability switched

Fig. 3. Hourly mean change rate and variability of $\text{PM}_{2.5}$ concentrations in different hourly rainfall sectors during 2014–2016 for (a) Wushan, (b) Luogang, (c) Panyu, and (d) Huadu sites, and (e) four-site average.

to be negative, indicating that the local air quality was in the clean mode which was favorable for the $\text{PM}_{2.5}$ removal. The balanced wind speed varied at different sites, with 2.4, 2.2, 1.8, and 1.2 m s^{-1} for Wushan, Luogang, Huadu, and Panyu sites, respectively. The critical value at Wushan site was the highest among these four sites. This site is located in downtown with serious pollution, which calls for higher wind speed to transport or diffuse the fine particles. Panyu site had the lowest critical value of wind speed, which could be due to its location in suburban areas with lower emissions. The results of wind speed in this study have important implications for air quality control. Taking Luogang as an example, when the wind speed ranged from 1.8 to 3.0 m s^{-1} , its capability to remove particles was limited and the $\text{PM}_{2.5}$ concentration would decline at a low rate. In this meteorological condition, strict emission control is needed in case of the occurrence of heavy pollution. When the horizontal wind speed $> 3 \text{ m s}^{-1}$ the $\text{PM}_{2.5}$ concentration

Fig. 4. Hourly mean change rate and variability of $PM_{2.5}$ concentrations in different wind speed sectors during 2014–2016 for (a) Wushan, (b) Luogang, (c) Panyu, and (d) Huadu sites, and (e) four-site average.

would decline significantly, indicating that the horizontal transmission can quickly remove fine particles. No emergency measures for emission control are needed in this situation.

3.1.4 Wind direction and its frequency

Besides wind speed, the wind direction is also an important meteorological parameter affecting $PM_{2.5}$ concentration (Wang and Ogawa, 2015; Zhang *et al.*, 2015). Fig. 5(a) presents the variability of $PM_{2.5}$ concentration, frequency, and contribution rate in different wind directions. The contribution rate was calculated by the variability of $PM_{2.5}$ concentration multiplying the frequency of wind direction. Under the calm wind, $PM_{2.5}$ concentration had a high negative variability. However, the contribution rate of the calm wind to the overall $PM_{2.5}$ concentration was not obvious due to its low wind frequency. The southeasterly wind had a higher negative

Fig. 5. (a) The four-site-averaged hourly PM_{2.5} variability, frequency of wind direction, and contribution rate of variability (variability multiplies frequency of wind direction) in different wind directions during 2014–2016. C denotes the calm wind. (b) is the same as (a) but for MDA8 O₃ variability.

contribution to PM_{2.5} variability, which indicated lower PM_{2.5} concentrations under this wind direction. The north wind appeared in the highest frequency, but it had a lower negative contribution to PM_{2.5} variability. The north-northeast and south-southwest wind contributed the most to the positive PM_{2.5} variability.

Fig. 6 shows the wind rose of hourly PM_{2.5} concentration, illustrating the relationship between the concentration and wind speed and wind direction. For the dominant wind direction, it is northerly at Huadu and Luogang sites, northerly and southeasterly at the Panyu site, and northerly, southerly, and easterly at the Wushan site. At the Luogang site, the PM_{2.5} concentration was lower than the other sites due to its location in suburban areas. The critical value of wind speed can be used as an indicator to identify the importance of local emission and regional transport to the pollutant concentrations. Under the wind from the east, southeast, south, and southwest, the concentration at wind speed < 2.2 m s⁻¹ (the balanced wind speed at this site) was higher than that at wind speed > 2.2 m s⁻¹, which indicated that the local emission contributed most to the high PM_{2.5} concentration in this condition. Under the winds from the north, northwest and west, PM_{2.5} concentration would be higher and the difference in concentrations was small at lower and higher wind speed, which suggested that the Luogang site would experience serious PM_{2.5} pollution no matter affected by local emissions or regional transport. At the Panyu site, the PM_{2.5} concentration would be higher under the northwesterly wind. In view of the lower critical value of wind speed at this site (1.2 m s⁻¹), both the local emission and regional transport (from the center of Guangzhou and Foshan cities) were important sources of severe PM_{2.5} pollution. At the Wushan site, the PM_{2.5} concentration would

Fig. 6. The wind rose of hourly $\text{PM}_{2.5}$ concentrations at Wushan, Luogang, Panyu, and Huadu sites. The different color in the figure denotes the $\text{PM}_{2.5}$ concentrations, and the black solid line denotes the wind frequency.

be higher with low wind speed ($< 2.4 \text{ m s}^{-1}$) under the westerly wind, which suggested that this site was more influenced by local emission from downtown area than long range transport. At the Huadu site, the $\text{PM}_{2.5}$ concentration was higher at lower wind speed than at higher wind speed in all directions, which implied that the $\text{PM}_{2.5}$ pollution at this site was controlled by local emissions.

In the combination of wind direction and wind frequency, we found that the frequency of west wind was low. However, there were high $\text{PM}_{2.5}$ concentrations at Huadu, Panyu, Wushan and Luogang sites under the westerly wind, which suggested that Guangzhou was likely to suffer from severe $\text{PM}_{2.5}$ pollution in this condition.

3.2 Modulation by Meteorological Parameters of O_3

3.2.1 Sunshine duration

Ozone is a secondary pollutant produced by photochemical reactions, and its concentration is positively correlated to the sunshine duration (Zhang *et al.*, 2015). Fig. 7 presents the variability and change rate of MDA8 O_3 concentration in different sunshine duration sectors by an interval of 1 hour. The change rate was more significant with high sunshine duration. The critical values of sunshine duration for Wushan (4 hours), Panyu (4 hours), Luogang (3 hours), and Huadu (3 hours) sites were obtained, and there is little difference between them. For the four-site average, the critical value in Guangzhou is 4 hours. When the sunshine duration > 4 hours, the O_3 variability was positive and favorable for the increase in concentrations, which reflects that the ozone formation is positively correlated with illumination. When the sunshine duration ranges from 6 to 10 hours, the positive variability of O_3 concentration reaches the peak. However, when the sunshine duration $\leq$ the critical value (~ 4 hours), the O_3 variability switches to be negative, which tends to decrease ozone concentrations. This negative variability could be attributed to the cloudy weather in a day with short sunshine duration, which is adverse to the ozone formation.

Fig. 7. Daily mean change rate and variability of MDA8 O₃ concentrations in different sunshine duration sectors during 2014–2016 for (a) Wushan, (b) Luogang, (c) Panyu, and (d) Huadu sites, and (e) four-site average.

3.2.2 Daily maximum temperature

The higher maximum daily temperature is conducive to the O₃ formation (Toh *et al.*, 2013; Zhang *et al.*, 2015). Fig. 8 depicts the variability and change rate of MDA8 O₃ concentration in different sectors of maximum daily temperature by 1°C interval. High change rate with high temperature, but is not the higher the temperature the greater change rate. The critical value of maximum daily temperature in Guangzhou is 29°C, and there was little difference between the four sites (29°C for Luogang, 29°C for Panyu, 28°C for Wushan, and 28°C for Huadu). On the result of the four-site average, when the maximum daily temperature > 29°C, the O₃ variability was positive and favorable for the increase in O₃ concentrations. High O₃ concentration occurred when the temperature ranges from 32°C to 36°C. When the maximum daily temperature ≤ 29°C, the O₃ concentration variability was negative and conducive to O₃ reduction.

Fig. 8. Daily mean change rate and variability of MDA8 O₃ concentrations in different maximum daily temperature sectors during 2014–2016 for (a) Wushan, (b) Luogang, (c) Panyu, and (d) Huadu sites, and (e) four-site average.

3.2.3 Daily mean wind speed

The magnitude of the horizontal wind speed plays a very important role in the diffusion and dilution of ozone concentrations (Zhang *et al.*, 2015). Fig. 9 shows the variability and change rate of MDA8 O₃ concentration in different average daily wind speed sectors by 0.2 m s⁻¹ interval. For the four-site average, the balanced wind speed of O₃ variability was 1.8 m s⁻¹, which was comparable with that of PM_{2.5} variability and change rate, reflecting the similar role of wind speed in the variation and change rate of O₃ and PM_{2.5} concentrations. The difference of the critical value among four sites was small, with 1.8 m s⁻¹ (Huadu), 1.8 m s⁻¹ (Luogang), 1.8 m s⁻¹ (Wushan), and 1.6 m s⁻¹ (Panyu). In Guangzhou, when the average daily wind speed > 1.8 m s⁻¹, the variability of O₃ concentration was negative and it tended to decrease. When the average daily wind speed ranged from 2.0 to 3.0 m s⁻¹, the reduction of O₃ concentration was most

Fig. 9. Daily mean change rate and variability of MDA8 O₃ concentrations in different average daily wind speed sectors during 2014–2016 for (a) Wushan, (b) Luogang, (c) Panyu, and (d) Huadu sites, and (e) four-site average.

significant, indicating that the level of transmission could decrease O₃ effectively. When the average daily wind speed $\leq 1.8 \text{ m s}^{-1}$, the O₃ concentration variability was positive, which was favorable for the rise in O₃ concentration.

3.2.4 Wind direction and its frequency

The effect of wind direction on the ozone concentration cannot be ignored (Toh *et al.*, 2013). Fig. 5(b) presents the variability of O₃ concentration, frequency, and contribution rate in different wind directions. It is shown that the northwest wind contributed most to the positive O₃ variability, while the southeast wind contributed most to the negative O₃ variability. The most frequent north wind contributed little to the negative O₃ variability. The calm wind had the lowest frequency, and also contributed little to the positive ozone variability.

Fig. 10 depicts the relationship between hourly ozone concentrations and near-surface wind

Fig. 10. The wind rose of hourly O_3 concentrations (11:00–18:00) at Wushan, Luogang, Panyu, and Huadu sites. The different color in the figure denotes the O_3 concentrations, and the black solid line denotes the wind frequency.

speed and wind direction in the four sites of Guangzhou. Only the samples between 11:00 and 18:00 were taken into account due to the generally high O_3 concentrations during this period in a day. For the four sites, we found that the O_3 concentration at wind speed $> 1.8 \text{ m s}^{-1}$ (the critical value) was generally higher than that at wind speed below the critical value, especially at the Wushan site, which indicated that the regional transport was more important than the local emission for O_3 formation in Guangzhou. At the Panyu, Luogang and Huadu sites, the O_3 concentration was higher under the westerly wind at higher wind speed ($> 1.8 \text{ m s}^{-1}$). The regional transport of O_3 and its precursors from the urban center of Foshan and Guangzhou city could be responsible for this high O_3 concentration. At the Wushan site, the O_3 concentration was higher under the winds from the west at higher wind speed, which indicated the significant contribution of regional transport to ozone pollution. In addition, similar to the results for $PM_{2.5}$ discussed above, Guangzhou was also likely to suffer from severe ozone pollution under the westerly wind.

4 MODULATION BY METEOROLOGY OF THE INTERANNUAL $PM_{2.5}$ AND O_3 CONCENTRATION

Fig. 11 shows the annual average $PM_{2.5}$ and O_3 concentration from 2014 to 2016 in Guangzhou. The decrease in $PM_{2.5}$ concentrations was found during these three years, which can be explained by the strict emission control measures implemented in Guangzhou (Gao *et al.*, 2016). For the interannual variation of O_3 concentration, it was highest in 2014, then decreased in 2015 and leveled off in 2016.

The interannual variation of these two pollutants could also be affected by the changes in meteorological conditions. According to the study above, the critical values of relative humidity, hourly rainfall intensity, hourly wind speed, sunshine duration, maximum daily temperature, and mean daily wind speed for major pollutant concentrations ($PM_{2.5}$ and O_3) in Guangzhou were

obtained. These critical values were used as indicators to evaluate the favorability of meteorological conditions to air quality in the past three years (2014–2016). Fig. 12 shows the proportions below and above these critical values from 2014 to 2016. On the impacts of meteorological parameters on $\text{PM}_{2.5}$ concentration, the proportion below the critical value of relative humidity slightly decreased from 2014 to 2016, which suggested the relative humidity in 2014 tended to decrease the concentrations. However, the proportions below the critical value of hourly rainfall intensity (0.6 mm hour^{-1}), and below the critical value of hourly wind speed (1.8 m s^{-1}) were significantly higher in 2014 than those in 2015 and 2016, which implied the more adverse effects of these two meteorological parameters on the decrease in $\text{PM}_{2.5}$ concentration. On the impacts of meteorological parameters on O_3 concentration, the proportions above the critical value of sunshine duration (4 hours), above the critical value of maximum daily temperature (29°C), and below the critical value of mean daily wind speed (1.8 m s^{-1}) were generally higher in 2014 than those in 2015 and 2016, which indicated that these meteorological parameters in 2014 were the most unfavorable for the reduction of O_3 concentrations. This indication was also suggested by Yin *et al.* (2019), who used the Kolmogorov-Zurbenko filter method to separate the variation of O_3 concentrations in Guangzhou induced by meteorological

Fig. 11. The annual average $\text{PM}_{2.5}$ and MDA8 O_3 concentrations during 2014–2016. The gray and green columns denote annual average $\text{PM}_{2.5}$ and MDA8 O_3 concentrations respectively.

Fig. 12. The proportions above or below the critical values of (a) relative humidity, (b) hourly rainfall intensity, (c) hourly wind speed, (d) maximum daily temperature, (e) sunshine duration, and (f) mean daily wind speed during 2014–2016.

changes. Some scholars established a comprehensive meteorological index to characterize the atmospheric diffusion capacity (Adam *et al.*, 2011). In order to help forecasters to comprehensively understand the critical values, we also established an integrated index to quantitatively evaluate the favorability of meteorological conditions for PM_{2.5} and O₃ pollution based on all these critical values. We used the following formula to calculate the integrated index for each year. The smaller the integrated index, the better the diffusion conditions.

$$PM_{\text{index}} = f(RH) \times f(Rainfall) \times f(ws) \quad (1)$$

$$Ozone_{\text{index}} = f(ss) \times f(Tmax) \times f(Daily\ ws) \quad (2)$$

In the formula, $f(RH)$ represented the probability that the relative humidity > 50%, $f(Rainfall)$ represented the probability that the hourly rainfall intensity < 0.6 mm, $f(ws)$ represented the probability that the hourly wind speed < 1.8 m s⁻¹; $f(ss)$ represented the probability that the sunshine duration > 4 hours, $f(Tmax)$ represented the probability that the maximum daily temperature > 29°C, $f(Daily\ ws)$ represented the probability that the daily wind speed < 1.8 m s⁻¹. The larger the index is, the worse the diffusion condition is. Analysis according to Fig. 12, the results showed the decline over the past three years for the index of PM_{2.5} (0.34, 0.28, and 0.27), the same trend for the index of O₃ (0.25, 0.24, and 0.21), and they all showed that the diffusion conditions is worst in 2014. Meteorological factors not only determine the ozone and PM_{2.5} generation reaction conditions, but also the transmission and distribution. It can be characterized the key meteorological factors of pollutant transport (horizontal wind), diffusion (integrated index) and sedimentation (rainfall intensity) and establish the threshold value, which provides the basis for the discrimination of pollution process.

In summary, based on the evaluation results using the critical values of meteorological parameters, we suggested that the meteorological conditions were the most unfavorable for better air quality in 2014 among these three years (2014–2016). The critical values of meteorological parameters obtained in this study worked successfully as indicators to evaluate the favorability of meteorological conditions.

5 CONCLUSION AND IMPLICATIONS

Our study used meteorological and air quality data collected from 2014 to 2016 in Guangzhou to evaluate the influence of significant meteorological parameters on the hourly PM_{2.5} concentration and the daily maximum 8-hour-averaged (MDA8) O₃ concentration by calculating each factor's critical values for these pollutant levels. The major conclusions are summarized as follows:

- 1) The hourly PM_{2.5} concentration tended to increase when the relative humidity was > 50%, the hourly rainfall intensity was ≤ 0.6 mm hour⁻¹, or the wind speed was ≤ 1.8 m s⁻¹ but otherwise decreased, whereas the MDA8 O₃ concentration tended to increase when the sunshine duration was > 4 hours, the maximum daily temperature was > 29°C, or the average daily wind speed was ≤ 1.8 m s⁻¹ but otherwise decreased.
- 2) The high levels of PM_{2.5} and O₃ at Panyu, Luogang, and Huadu were generally contributed by both local and transported emissions, whereas those at Wushan were mainly contributed by local emissions. In addition, although westerlies seldom arose, they co-occurred with greatly elevated concentrations at Luogang, Wushan, Panyu, and Huadu, indicating that wind from this direction is likely to result in PM_{2.5} or O₃ air pollution.
- 3) Applying the critical values of the relative humidity, hourly rainfall intensity, hourly wind speed, sunshine duration, maximum daily temperature, and mean daily wind speed for the PM_{2.5} and O₃ concentrations as meteorological indicators of air quality from 2014 till 2016 revealed that the weather conditions in 2014 were the least favorable during the study period. The integrated index also confirmed that 2014 exhibited the worst diffusion conditions of these three years.

Using Guangzhou as a case study, these results further our understanding of the relationship between weather conditions and pollutant concentrations. The critical values of the studied

meteorological parameters can be used to identify weather conditions that are favorable or unfavorable to air quality. Owing to variations in climate, the values obtained for Guangzhou may not be applicable in other regions. However, our methods can be employed to forecast the air quality from meteorological parameters.

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