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Atmospheric Chemistry and Physics Discussions

Impact of the COVID-19 pandemic on the observed vertical distributions of $PM_{2.5}$, NO_x, and O_3 from a tower in the Pearl River Delta

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Abstract. The outbreak of the 2019 novel coronavirus (COVID-19) has brought tremendous impact and influence on human health and social economy around the world. The lockdown implemented in China, starting on 23 January 2020, led to large reductions in human activities and the associated emissions. Sharp declines in primary pollution provided a unique chance to examine the relationships between anthropogenic emissions and air quality. Here, we report measurements of air pollutants and meteorological parameters at different heights on a tall tower in the Pearl River Delta, China, to investigate the response of the vertical scales of pollutants to reductions in human activities. Compared to the pre-lockdown period (starting from 16 December 2019), the observations showed that

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surface layer NO_x, $PM_{2.5}$ and mean values of the daily maximum 8 h average O_3 (MDA8O_3) had significant reductions of 76.8%, 49.4%, and 18.6% respectively, but the average O_3 increased (9.7%) during lockdown period. The vertical profiles of NO_x and O_3 changed during the lockdown period, but not those of $PM_{2.5}$. The correlation between $PM_{2.5}$ and O_3 was statistically significant, but not that between $PM_{2.5}$ and NO_x for data collected at four different heights during the lockdown period. The significance of these correlations was the opposite during the pre-lockdown period, indicating that the main composition of $PM_{2.5}$ has changed dramatically since the lockdown, which is transited from primary aerosol dominating or nitrate dominating (affected by NO_x) before lockdown to secondary organic aerosol dominant dominating (affected by O_3) during the lockdown. We find weaker diurnal variation of O_3 during the lockdown period is similar to the case at background regions. O_3 concentrations were not sensitive to NO_x concentrations during lockdown, which implies that O_3 levels during the lockdown are more representative of the regional background, for which anthropogenic emissions are low and photochemical formation is not a significant ozone source. This evidence suggests that significant reductions of anthropogenic emissions are effective in simultaneous mitigation of $PM_{2.5}$ and O_3 levels.

Keywords: COVID-19 induced Lockdown, $PM_{2.5}$, NO_x, O_3, Tower Observation

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic has completely changed the world and caused great losses of life globally. At present, over 200 countries and regions have been affected by the pandemic, and the numbers of infections and deaths caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and its variants are still rising (Wang et al., 2020). Many countries have chosen to implement lockdowns to bring the pandemic under control; that is, to cut off the spread of SARS-CoV-2 by reducing gatherings and maintaining social distancing among individuals. These measures have generally reduced human activity, decreasing or

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completely halting manufacturing work and the movement of people. Although the lockdowns have had devastating socioeconomic impacts, recent studies have shown them to be beneficial for the environment (Chakraborty and Maity, 2020).

The reduction in human activities due to the pandemic has greatly decreased the emission of primary pollutants. This, in turn, has caused significant impacts on regional air quality (Xing et al., 2020; Salma et al., 2020; Wang et al., 2021; Kim et al., 2021) and even climate (Gettelman et al., 2021), albeit differing from region to region. In South East Asia, the lockdown has led to a notable decrease in the aerosol optical depth over the region and in pollution outflow over the oceanic areas, while a significant decrease (27%–30%) in tropospheric nitrogen dioxide (NO_2) levels has been observed over territories not affected by seasonal biomass burning (Kanniah et al., 2020). Srivastava (2020) noted that the aerosol optical depth had been reduced by up to 50% over the Indo-Gangetic Plain during the lockdown period. In Italy, urban road traffic decreased by 48%–60% on average during the country's periods of implemented lockdowns, which greatly decreased the concentrations of NO_2 and particulate matter with aerodynamic diameter less than 10 μm (PM_{10}) and less than 2.5 μm ($PM_{2.5}$) (Gualtieri et al., 2020). Rodríguez-Urrego& Rodríguez-Urrego (2020) found that the average $PM_{2.5}$ concentration of the 50 most polluted capital cities in the world had decreased by 12% on average. By analysing the emissions data of 28 cities in the USA during its first round of lockdowns (15 March 2020 to 25 April 2020), it was found that 2 out of 3 cities showed greatly reduced NO_2 and carbon monoxide (CO) concentrations (with decreases up to 49% and 37%, respectively) compared with the 2017–2019 historical baseline and pre-lockdown levels. These decreases in NO_2 and CO concentrations also increased in proportion to the local population density. However, the $PM_{2.5}$ and PM_{10} concentrations only decreased significantly in north-eastern USA, California, and Nevada, which also recorded the largest decreases in NO_2 concentrations (Rodríguez-Urrego& Rodríguez-Urrego, 2020).

China was the first country in the world to report SARS-CoV-2 infections to the World Health Organization.

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The atmospheric environment of China was also significantly affected by the lockdown measures taken during the pandemic, with some studies showing the atmospheric NO_2 concentrations to have been greatly reduced. These reductions first occurred in Wuhan before spreading to the rest of China (Wang and Su, 2020). The Pearl River Delta (PRD) is one of the most important economic zones in China and is also one of the most rapidly urbanising regions in the world. The intensity of human activity in this region is also amongst the highest worldwide (Li et al., 2021). The PRD was once severely affected by air pollution, which manifested as increasingly frequent haze weather and rising PM concentrations. Because of the optimisation of industrial structures and implementation of increasingly stringent pollution control measures, the air quality over the PRD had already been improved significantly over the past decade (Zhang et al., 2015). Nonetheless, because the PRD contains immense transportation networks and a dense distribution of factories, it has been difficult to stamp out pollutant emissions completely. Therefore, the nitric oxide (NO_x), $PM_{2.5}$, and ozone (O_3) concentrations in the PRD often spike because of unfavourable weather conditions (Li et al., 2020). The pandemic lockdowns have greatly reduced the intensity of human activities in the PRD in a very short time, which has created a rare opportunity for the study of air pollution mechanisms in the area.

Ever since the advent of the COVID-19 pandemic, numerous scholars have used this unique window of opportunity to gain important insights into the mechanisms of air pollution. However, most of these studies were based on ground-level data or space-based measurements of atmospheric column concentrations. By contrast, there are no reports about the vertical distribution of air pollutants during the COVID-19 pandemic period. The vertical distribution of air pollutants is a crucial piece of the puzzle for understanding how air pollution events are formed. Meteorological towers are by far the most useful platforms for studies about the vertical distribution of near-surface pollutants. Unlike tethered balloons or drones, meteorological platforms can be used to obtain continuous and stable measurements over a long period of time. Numerous such studies have previously been performed using the

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325-m-tall meteorological tower in Beijing (Meng et al., 2008; Sun et al., 2010; Sun et al., 2013) and the 300-m-tall tower in Boulder, USA (Brown et al., 2013).

The PRD has one meteorological tower, the Shenzhen Meteorological Gradient Tower (SZMGT). The monitoring equipment on this tower can be used to measure several air quality factors, including $PM_{2.5}$, NO_x, and O_3 concentrations. Li et al. (2020) had analysed the vertical distribution of pollutants in the PRD during the peak pollution season, based on air quality data and meteorological data obtained at the SZMGT from December 2017. This provided useful insights about the vertical structure of air pollutant distribution in the PRD. Shenzhen is a very developed city with active human activities (Li et al., 2015) and is facing the problem of air quality (Yang et al., 2020). As the beginning of the COVID-19 pandemic coincided with the peak pollution season of the PRD, data on the vertical distribution of pollutants recorded by the SZMGT during this period are invaluable for revealing how a decrease in human activity may affect pollutant concentrations.

2. Data and Methods

The observational data, from 16 December 2019 to 15 February 2020, used in this study were from a meteorological observation base on the east side of the Pearl River estuary; namely, the Shiyan Meteorological Observation Base (hereinafter Shiyan Base), managed by the Shenzhen National Climate Observatory (Fig. 1a). The base, which lies approximately 10 km from the coastline, is in the woodland area surrounding a reservoir. Because the reservoir is an important source of drinking water for the population of Shenzhen, the environment within 1 km around the SZMGT is protected by law and is rarely disturbed by human activity, ensuring that the underlying surface will remain natural for a long time.

The entire area of Shenzhen is located within the subtropical monsoon climate zone. The dominant wind direction in summer is south, and the airflow brings clean air from the sea to the base. In winter, the dominant wind

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direction changes to a northerly one, and the airflow carries pollutants from the inland of the PRD to the base (Li et al., 2020). The peak of the COVID-19 pandemic occurred mainly in winter, a period when the meteorological conditions are generally unfavourable to the atmospheric environment of Shenzhen.

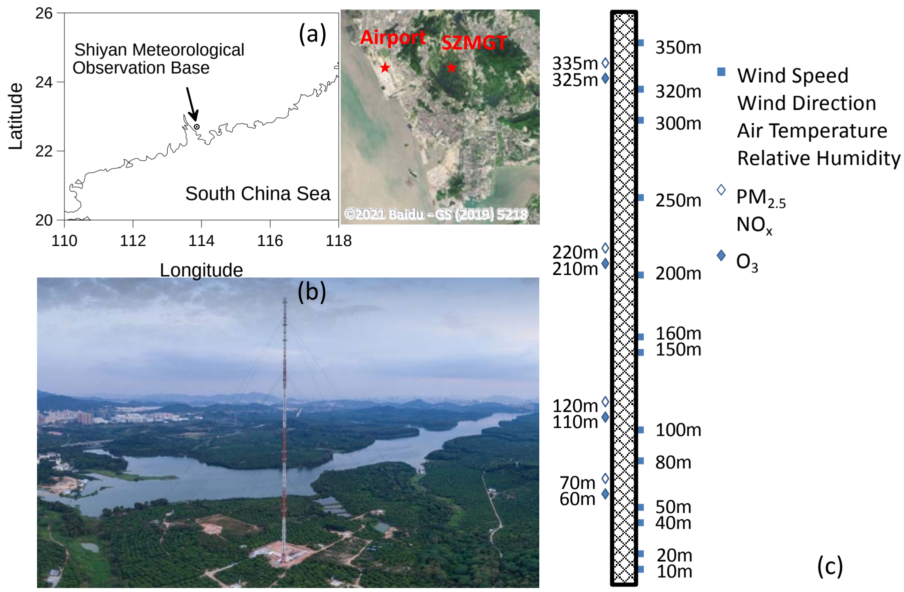

Fig. 1. Location of the Shiyan Meteorological Observation Base and Shenzhen meteorological gradient tower (SZMGT): (a) Location of the Shiyan Meteorological Observation Base; (b) Arial view of the meteorological tower; (c) Layout of the air quality and meteorological observation on the tower.

The SZMGT, which is 365 m tall (Fig. 1b), has 13 layers of meteorological observation platforms, starting from 10 m up to 350 m (Fig. 1c). Four of those layers (i.e. at 60–70, 110–120, 210–220, and 325–335 m, respectively) are atmospheric environmental observation platforms (Fig. 1c). The distance from the SZMGT to the nearest built-up area is approximately 1 km. At 800 m north-east of the Shiyan Base, there is a busy highway from which pollutants emitted by the vehicles passing through could influence the observational data on the tower. There is also an airport located approximately 10 km west of the base which serves an estimated 356,000 flights in a

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normal year. Thus, the airplanes taking off and landing at the airport also potentially influence the pollutant concentration data recorded by the SZMGT (Li et al., 2020). An additional atmospheric environmental observation station lies at the bottom of the SZMGT. Because this station is located on the ground, the height of its sampling port is lower than that of the surrounding forest top.

The meteorological data used in the current study were collected at all 13 platform heights, as shown in Fig. 1c. The environmental data were collected at the heights of 110–120, 210–220, and 325–335 m. The data at the height of 60–70 m was not included in the analysis owing to the occurrence of equipment failure during the pandemic. Data from the atmospheric environmental observation station at the bottom of the SZMGT were also used in the current study.

The following are the equipment used at the SZMGT for sensing wind, temperature and humidity, and visibility, respectively: the Vaisala WMT700 Ultrasonic Wind Sensor, Vaisala HMP155 Humidity and Temperature Probe, and Vaisala PWD Present Weather Visibility Sensor. $PM_{2.5}$ concentration data are collected by Thermo Scientific™ 5030i Sharp Particulate Monitoring equipment, NO_x by the Thermo Scientific™ 42i Gas Analyzer, and O_3 by the Thermo Scientific™ 49i Gas Analyzer. The data from the various instruments were downloaded at a frequency of once every 5 minutes. Arithmetic averaging of the data was performed for all the elements, except for the wind direction, to obtain hourly average data. The daily average data by arithmetic averaging were obtained using the hourly average data over 24 hours. For determination of the wind direction, representative values were obtained by calculating the highest wind frequency by the hour and by the day.

3. Results and Discussion

3.1 Change of Pollutants Concentrations and Meteorological Elements

Fig. 2 shows the daily mean concentrations of $PM_{2.5}$, O_3, and NO_x observed at Shiyan Base in Shenzhen from

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16 December 2019 to 15 February 2020, as well as the daily mean relative humidity (RH), daily mean temperature, daily mean wind speed, and daily dominant wind direction of this period. Two key dates have been marked with blue dotted lines on the $PM_{2.5}$, O_3, and NO_x graphs: 15 January 2020 and 23 January 2020. The first case of COVID-19 in Shenzhen was reported by local news outlets on 15 January 2020. The Shenzhen government reacted very quickly to this news, despite the low number of patients with COVID-19 in the area at the time. The news was immediately published on the official Shenzhen government website and social restriction measures were implemented. On the advice of medical experts, a lockdown was imposed on Wuhan on January 23rd. The Guangdong province, where Shenzhen is located, also activated its top-level emergency response on this day, and all residents in Shenzhen and her neighbouring cities were instructed not to leave their homes unless necessary. Therefore, after news about the COVID-19 pandemic first appeared on January 15th, the intensity of human activity in Shenzhen (both manufacturing and traffic) began to decrease. By January 23rd, Shenzhen was virtually shut down because of the strengthening of activity restrictions. Other than the most vitally important logistics chains, very little traffic remained on the streets. Owing to a lack of data, it has not been possible to quantitatively estimate the degree to which human activity decreased in Shenzhen during this period. Nonetheless, air traffic at the airport west of Shiyan Base could provide some indication of the scale. In news reports, it was mentioned that the number of passengers at the airport had decreased by as much as 79.49% in February 2020. Since February usually coincides with the Spring Festival (Chinese New Year), this decrease in passenger volume is enough to describe the magnitude by which human activity decreased in this region.

As shown in Figs. 2a and 2c, the daily mean concentrations of $PM_{2.5}$ and NO_x closely tracked the lockdown-mediated change in human activity. Since there were no cases of COVID-19 in Shenzhen before 15 January 2020, the local government did not impose any restrictions during the period between December 16th, 2019 and January 15th, 2020 and the pollutant concentrations remained high. After the first report of COVID-19 on

January 15th, many residents began to reduce the frequency of their outdoor activities owing to awareness of the pandemic. Since these reductions in human activity were voluntary and not universal, the pollutant concentrations only decreased slowly. However, the widespread implementation of high-level restrictions on January 23rd led to drastic and sustained reductions in pollutant concentrations. The daily mean concentrations of $PM_{2.5}$ and NO_x generally remained low after January 23rd, and their ranges of variation also became significantly narrower. Although all three measured pollutants were reduced by the lockdown, the change in NO_x was the most substantial. This is because NO_x is primarily derived from traffic emissions, and since the decrease in human activity also decreased traffic emissions, the concentration of NO_x in the atmosphere decreased instantaneously upon the cessation of vehicular traffic. Meanwhile, although the daily mean concentration of O_3 did not change significantly after January 23rd (Fig. 2b), the daily range of variation in its concentration (i.e. the difference between the minimum and maximum O_3 concentrations in a day) did decrease significantly after this date.

The variations in daily mean temperature, daily mean RH, daily mean wind speed, and daily dominant wind direction during the study period are shown in Figs. 2d and 2e. As evident in Fig. 2d, the RH and temperature correlated strongly with each other, indicating that the dry air in the PRD comes predominantly from cold air masses. During the study period, cold fronts occurred on 26–27 December 2019, 12 January 2020, and 27–30 January 2020. Whenever a cold air mass passes over the Shiyan Base, the daily mean temperature and RH will decrease in step with each other. As evident in Fig. 2e, the daily mean wind speeds of the study period were usually below 2 m/s. Additionally, the daily dominant wind direction was in the northerly direction for approximately 75% of the time. The weather that was observed during the study period is common during the winters in Shenzhen, indicating that no meteorological abnormalities had coincided with the study period. When we compared the variations in each meteorological factor against the pollutant concentrations, only the RH and O_3 concentration were found to be significantly (negatively) correlated with each other. The daily mean concentrations of $PM_{2.5}$ and

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NO$_x$ were not significantly correlated with any meteorological factor during the study period.

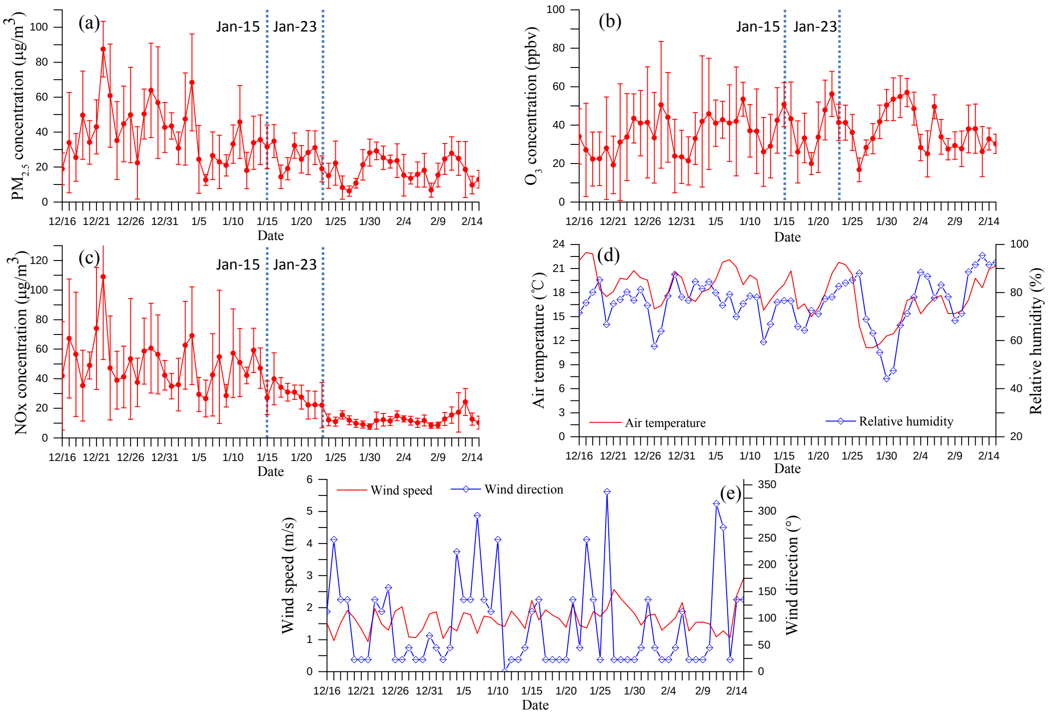

Fig. 2. Daily variations in pollutant concentrations and related meteorological factors in the surface layer during the period of 16 December 2019 to 15 February 2020: (a) PM$_{2.5}$ concentrations, (b) O$_3$ concentrations, and (c) NO$_x$ concentrations observed at different heights; (d) Air temperature and relative humidity observed at Shiyan Meteorological Observation Base; (e) Wind speed and wind direction observed by the auto weather station at Shiyan Meteorological Observation Base. ppbv means parts per billion by volume.

Taking 23 January 2020 as a date boundary, Fig. 3 compares the average concentrations of the 3 pollutants before and during the lockdown. Fig. 3 clearly illustrates the decrease of PM$_{2.5}$ and NO$_x$, during the lockdown. The decrease of NO$_x$ is much more drastic than that of PM$_{2.5}$. The change of O$_3$ is more complex than that of PM$_{2.5}$ or

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NO_x. The daily average O_3 concentration had slightly increased during the lockdown, which is consistent with the findings of other studies (Gualtieri et al., 2020). While the mean values of the daily maximum 8 h average O_3 (MDA8O_3) had significantly decreased during the lockdown. The definition of MDA8O_3 is as follows: in a natural day, take 0:00, 1:00,..., 16:00 local standard time (LST) as the starting point respectively, calculate the average concentration of O_3 for 8 consecutive hours for each starting point, and one can obtain totally 17 8-hour-average O_3 concentrations. The maximum value of all the 8-hour-average concentrations is MDA8O_3, which is generally used to assess the severity of O_3 pollution. The truth that daily O_3 concentration and MDA8O_3 had different changes means there might be quite different chemical environments related to O_3 before and during the lockdown.

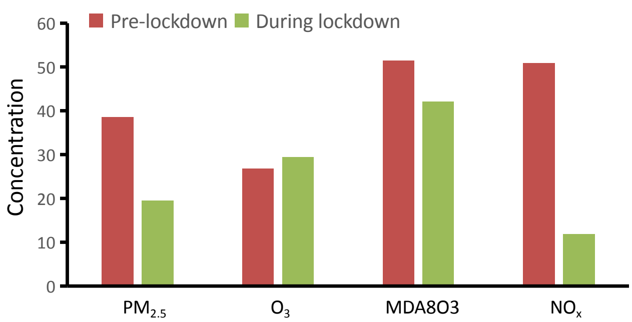

Fig. 3. Comparison of the average values of the $PM_{2.5}$ (in μg/m^3), O_3 (in ppbv), MDA8O3 (in ppbv) and NO_x (in μg/m^3) concentrations of the whole surface layer before and during the lockdown

Table 1 furtherly compares the average values of the meteorological factors and pollutant concentrations during and before the lockdown and those in the December of 2017 (Li et al., 2020). In the pre-lockdown period, the air quality in the area where the SZMGT is located had already been significantly improved compared with December 2017, which is reflected in the decrease of the average concentrations of the three pollutants.

Table 1 also provides the information on the changes of meteorological factors. In December 2017, the relative

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humidity was lower than that in the period of the current study, which was more favorable to the photochemical reactions generating $PM_{2.5}$ and O_3. On the other hand, the wind speed in December 2017 was much higher than that in the period of the current study, which was favorable to disperse the pollutants. Thus, it is difficult to compare the comprehensive impacts of the meteorological conditions on the pollutant's concentrations in December 2017 with those in pre-lockdown or during-lockdown period.

Table 1. Comparison of pollutants and meteorological elements during lockdown, before lockdown and December 2017

Time period	December 2017	Before 23 Jan. 2020	After 23 Jan. 2020	Change of pre-lockdown compared with December 2017	Change during lockdown compared with before lockdown
$PM_{2.5}$ (μg/m^3)	47.0	38.5	19.5	-18.1%	-49.4%
O_3 (ppbv)	42.0	26.8	29.4	-36.2%	+9.7%
MDA8O_3(ppbv)	59.6	51.4	42.1	-13.8%	-18.6%
NO_x (μg/m^3)	54.2	50.9	11.8	-6.1%	-76.8%
Air temperature (℃)	17.1	18.9	16.5	10.5%	-12.7%
Relative humidity (%)	58.5	75.3	77.0	+28.7%	+2.3%
Wind speed (m/s)	2.2	1.6	1.8	-27.3%	+12.5%
Wind direction	NNE	NNE	NNE	—	—

* NNE means north-north-east. All pollutant concentrations in the table are average values for the whole surface layer recorded by the tower.

While, at least one of the possible reasons leading to the decrease of pollutants concentrations in the pre-lockdown period compared with December 2017 is quite clear, which is the strengthening of pollution emission control in Shenzhen in the past 2 years. For example, according to local news reports, in 2019 more than 1000 heavy-duty diesel trucks in Shenzhen were replaced by electric trucks. In the past, the emissions of these diesel

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trucks were an important source of pollution in Shenzhen.

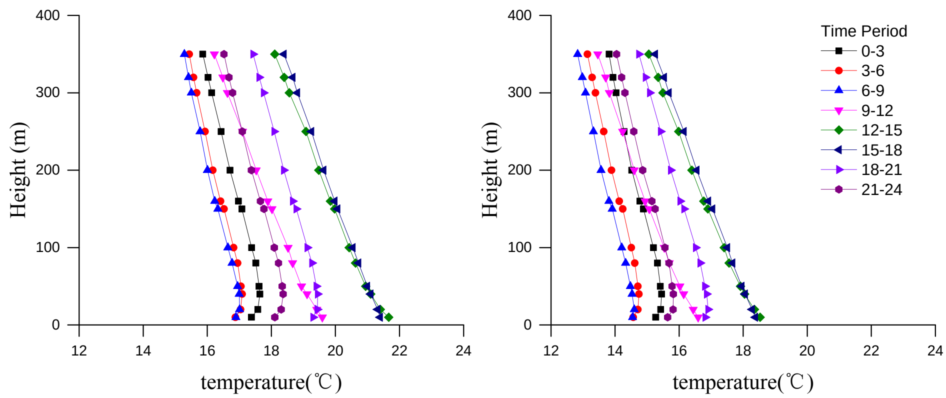

Fig. 4. Average vertical air temperature profiles recorded by the Shenzhen Meteorological Gradient Tower before and after 23 January 2020.

The changes in the meteorological factors during the lockdown compared with pre-lockdown period may largely be attributed to the intense cold air front that developed on 27–30 January 2020, which decreased the mean temperature of the lockdown period. By contrast, the RH changed very little after the lockdown was implemented. The meteorological factors that were most closely related to pollutant dispersal in the Shenzhen region were the wind speed and wind direction. Although the average wind speed increased during the lockdown, it was still weaker than that in December 2017 and never exceeded 2.0 m/s, thereby limiting any improvement in pollutant dispersion. The dominant wind direction in the pre-lockdown and lockdown periods was north-north-east, indicating that the winds in Shenzhen came mainly from the inland regions of China. In a normal year, these winds would carry a large amount of air pollution from the inland parts of the PRD and thus cause a spike in pollutant concentrations (Li et al., 2020). Therefore, it can be concluded that the meteorological conditions of the Shenzhen region were largely identical before and during the lockdown. Although an intense cold spell occurred after January 23rd and the average wind speed had increased slightly, it can be learnt from the experience that these changes would not be nearly enough to cause the dramatic decreases in average $PM_{2.5}$ and NO_x concentrations recorded. Figure 4 furtherly provides the average vertical air temperature profiles recorded by SZMGT before and after 23 January 2020, from which it can be found that there is no significant difference in the stratification of air temperature before and after the outbreak of the pandemic. The data illustrated in Table 1 and Fig. 4 show that the drastic change of the pollutant concentration in the study period is almost impossible to be caused by the change of meteorological factors.

3.2 Diurnal Variations at Different Heights

Figure 5 shows the diurnal variations in $PM_{2.5}$, NO_x, and O_3 concentrations on the surface (2 m) and at three different heights of the SZMGT (120, 220, and 335 m) before and during the lockdown. The $PM_{2.5}$ time series curves in Fig. 5a are characterised by two trends: a bimodal distribution for the ground level (2 m) and 120 m curves, and a unimodal distribution for the 220 m and 335 m curves. The peaks of the bimodal curves occurred at 09:00LST and 20:00 LST, which correspond roughly to the morning and evening rush hours. The difference between the $PM_{2.5}$ curves at 0 m/120 m and that of 220 m/335 m probably reflects the uplift process of the mixing layer top in this area. During night and early morning, the height of the mixing layer top is between 120m and 220m, so the curves of the upper and lower layers are quite different. After the noon time, with the rise of the mixing layer top, the curves of all layers become to be similar. Although the $PM_{2.5}$ concentrations at 2 and 120 m followed the same qualitative trend, the values on the ground were generally lower than those at 120 m. This may have been caused by the presence of dense forests near the ground observation point (Shiyan Base), which may have obstructed the dispersal of particulate matter and thus reduced the apparent $PM_{2.5}$ concentration. The peaks of the unimodal 220 and 335 m curves occurred at 17:00–19:00 LST. Therefore, the diurnal variations in $PM_{2.5}$ concentration were different at lower and higher heights. This is consistent with the findings of Li et al. (2020), whose study implied that high- and low-height $PM_{2.5}$ may have different sources. High-height $PM_{2.5}$ is formed predominantly by chemical reactions, whereas low-height $PM_{2.5}$ may be derived from multiple sources (predominantly surface-level primary emissions).

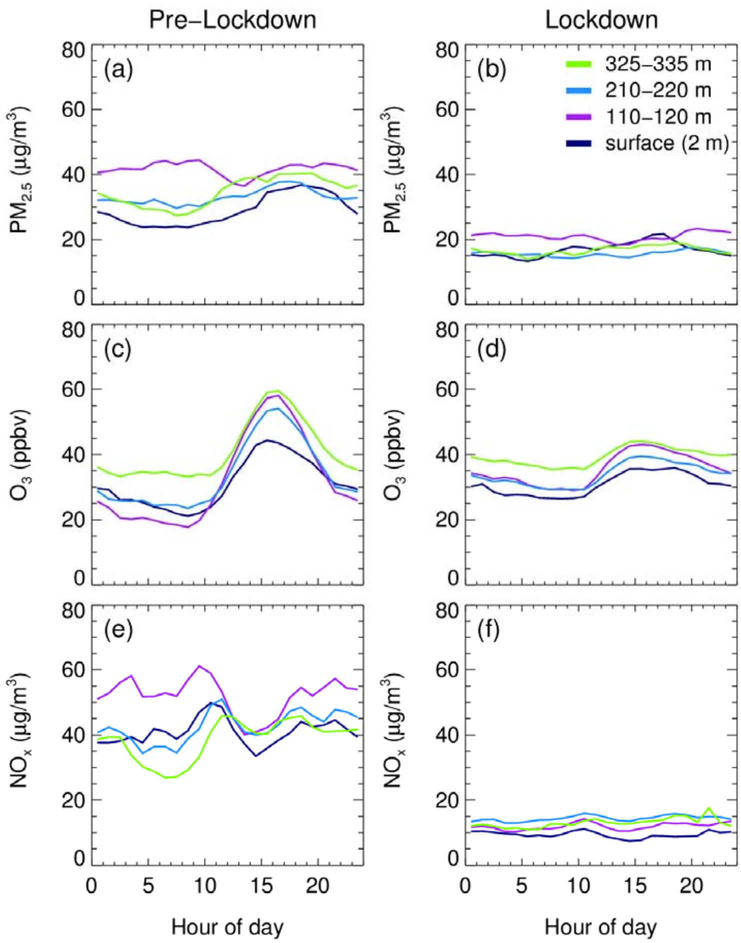

Fig. 5. Diurnal variations in the pollutants observed at different heights of the meteorological tower: $PM_{2.5}$ concentrations before lockdown (a) and during lockdown (b); O_3 concentrations before lockdown (c) and during lockdown (d); NO_x concentrations before lockdown (e) and during lockdown (f).

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The diurnal variations in $PM_{2.5}$ concentration at 2, 120, 220, and 335 m during the COVID-19 lockdown are shown in Fig. 5b. It was obvious that the $PM_{2.5}$ concentration had decreased significantly at all heights after January 23rd. The 120 m curve still had the highest $PM_{2.5}$ concentration and it still retained the bimodal structure of its pre-lockdown counterpart. The $PM_{2.5}$ concentrations at 220 and 335 m were still unimodal, and the peak still occurred at a similar time. The biggest lockdown-mediated change in $PM_{2.5}$ concentration occurred at 2 m, where the curve lost its peak in the morning and changed from a bimodal to a unimodal graph. It is likely that the morning peak of the pre-lockdown curve was caused by direct emissions from nearby human activities. These emissions were therefore greatly reduced by the lockdown-mediated decrease in human activity and were more easily blocked by the dense forest around the ground observation point.

With regard to O_3, it was evident that the diurnal variation in its concentration was unimodal and peaked at approximately 15:00–16:00 LST (when photochemical O_3 formation is most active) both before and during the lockdown (Figs. 5c and 5d, respectively). These diurnal variations were also qualitatively invariant with altitude; that is, only the average concentration varied from one altitude to the other. However, the shape of the O_3 curve did become significantly flatter during the lockdown, indicating that the range of the diurnal variations became much narrower during the lockdown. The flattening of the peaks and valleys of the O_3 curve implies that the chemical reactions that generate O_3 during day-time and consume O_3 during night-time became to be mush inactive during the lockdown. Under this condition, the O_3 concentration seemed to be determined primarily by background O_3 concentration (Xu et al., 2020). While, it should be noted that a flatter O_3 curve means the decrease of MDA8O_3, which implies that the prevention of O_3 and $PM_{2.5}$ pollution can be realized at the same time theoretically.

In the case of NO_x, the diurnal variations in its concentration were bimodal before the lockdown (Fig. 5e). The 2 and 120 m curves showed a peak at 09:00 LST, which coincided with the timing of the morning rush hour. The second peak, which begins at 18:00 LST and continues until 21:00 LST, was likely caused by the evening rush hour

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and the night-time decrease in the altitude of the mixed layer. The first peak in both the 220 and 335 m curves lagged the first peak of the curves of lower altitude by 1 hour. However, the second peak occurred at roughly the same time in both sets of curves. Although the mean NO_x concentrations had decreased significantly during the lockdown, their diurnal variations were still bimodal (Fig. 5f). However, inter-altitude differences in NO_x concentration did become much smaller during the lockdown and the timing of the NO_x peaks at each altitude also became much closer to each other. During the lockdown, the first peak was delayed by 1 hour while the second peak occurred at 17:00–19:00 LST. The NO_x concentrations also changed in another significant way; that is, they were lower at 2 and 120 m than at 220 and 335 m. Since NO_x is a primary pollutant, its significantly lower concentrations at the low altitudes implies that near-ground chemical reactions consume it more rapidly than the high-altitude chemical reactions do.

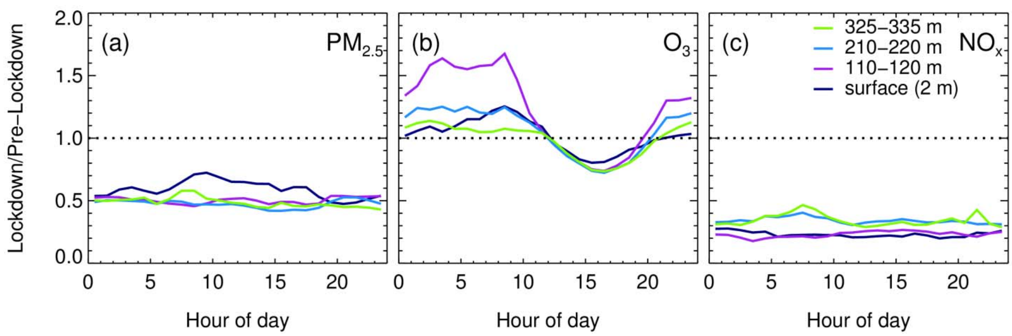

Fig. 6. Diurnal variations in the during-lockdown/pre-lockdown ratios of the pollutants observed at different heights of the meteorological tower: (a) $PM_{2.5}$; (b) O_3 and (c) NO_x.

In order to furtherly analyze the change of the pollutants during the lockdown, the concentration ratios of the pollutants before and during the lockdown are calculated, and the diurnal variation of the ratios is illustrated in Fig. 6. The diurnal variation curves of different pollutants had different characteristics. For NO_x, the curves at different

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heights were relatively consistent, which were relatively flat and maintained around 0.3, indicating that NO_x decreased significantly and evenly in the boundary layer. The curves for $PM_{2.5}$ were different. The ratio curves were relatively flat and maintained at about 0.5 all day at heights above 110 m, but there were relatively large fluctuations on the ground. The ratio on the ground increased significantly between 7:00 and 18:00 LST instead of keeping flat. Especially during 8:00 to 10:00 LST in the morning, the ratio value reached around 0.7, which showed that the decrease of ground level $PM_{2.5}$ concentration (~ -30%) during the morning "rush-hours" of lockdown was not as drastic as that of the average data of the whole boundary layer (~ -50%), though it was still difficult for the $PM_{2.5}$ generated on the ground to affect the air mass above 100 m. The fluctuation of ratio diurnal curves of O_3 was much more obvious than those of the other two pollutants. The ratios were generally greater than 1.0 in night and less than 1.0 in daytime, which showed that during lockdown, the concentration of O_3 increased in night and decreased in daytime. Especially at the height of 110-120 m, the fluctuation of the curve was more drastic, and the maximum ratio in night could reach 1.7. A possible reason leading to this phenomenon is that in the area where the SZMGT is located, the key height of night chemical reactions may be around 110-120 m. Under normal conditions, the night chemical reactions consuming O_3 in this layer may be more active than other heights. Therefore, when all emissions were weakened, the O_3 consumed by night chemical reaction was greatly reduced, and the O_3 concentration in this layer increases significantly. While this conjecture need further researches to confirm in the future.

3.3 Vertical Distribution of Pollutants

The changes in the vertical distribution of the 3 pollutants and total oxidants, Ox (= O_3 + NO_2), measured at 120, 220, and 335 m of the SZMGT before and during the lockdown are shown in Fig. 7. In terms of the all-day averages (Figs. 7a–7d), it was obvious that the $PM_{2.5}$, NO_x concentrations were lower at all altitudes during the lockdown. By contrast, the O_3 concentrations did not decrease significantly, but their vertical gradations did become less pronounced. Therefore, the O_3 concentrations became more uniform in the vertical direction during the lockdown. The Ox concentrations, both on daytime and nighttime average (Figs. 7h–7i), also were generally lower during the lockdown than that before the lockdown, indicating that the oxidation capacity for the whole boundary layer weakened during the lockdown. We also checked the nitrate radical production rate during the nighttime, which is an indicator of nighttime oxidation reactions, and showed a large decline with an average of ~70%, suggests the weaken NO_3 oxidation capacity. The decrease in nighttime oxidation is mainly attributed to cliff fall of NO_x. Overall, our vertical observation showed that the atmospheric oxidation processes, including photochemistry and nighttime chemistry were largely reduced due to the lockdown.

As shown in Fig. 7a, the $PM_{2.5}$ concentrations initially decreased with increasing altitude, before increasing slightly with further increases in the altitude. This trend occurred both before and during the lockdown period. The $PM_{2.5}$ concentration was the highest at the lowest observation point studied (i.e. 120 m), whereas the concentration at 335 m was between those recorded at 120 and 220 m. This observation is rather interesting, as it is contrary to the expectation that the $PM_{2.5}$ concentration should decrease monotonically with increasing altitude (Sun et al. 2010). However, this can be explained if we consider the results of previous studies about the possible sources of $PM_{2.5}$ at each altitude. At the lowest height (120 m), $PM_{2.5}$ may have come from photochemical reactions and primary pollution sources on the ground. At the middle level and above, $PM_{2.5}$ is formed mainly by photochemical reactions (Li et al. 2020). Therefore, the efficiency of $PM_{2.5}$ generation at these heights may be affected by the oxidative potential of the atmosphere. Based on the observations on the SZMGT, the O_3 concentration generally increases with increasing height, and the Ox is also higher at 335 m than at 220 m. Hence, it is likely that the oxidation capacity of the atmosphere is higher at the highest level, increasing the efficiency of $PM_{2.5}$ formation at this altitude. Although volatile organic compound (VOC) concentrations were not measured on the SZMGT, measurements in the nearby region of Taiwan have shown that these compounds also tend to increase with

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increasing altitude, up to a peak of 300–400 m, thus providing an ample supply of reactants for photochemical reactions at high altitudes (Vo et al., 2019). At the middle level (220 m), the $PM_{2.5}$ concentration is not significantly affected by primary pollutant sources on the ground, and the $PM_{2.5}$-forming photochemical reactions are also less efficient here than in the higher levels. Consequently, the $PM_{2.5}$ concentrations are lower in the middle level than in the high level.

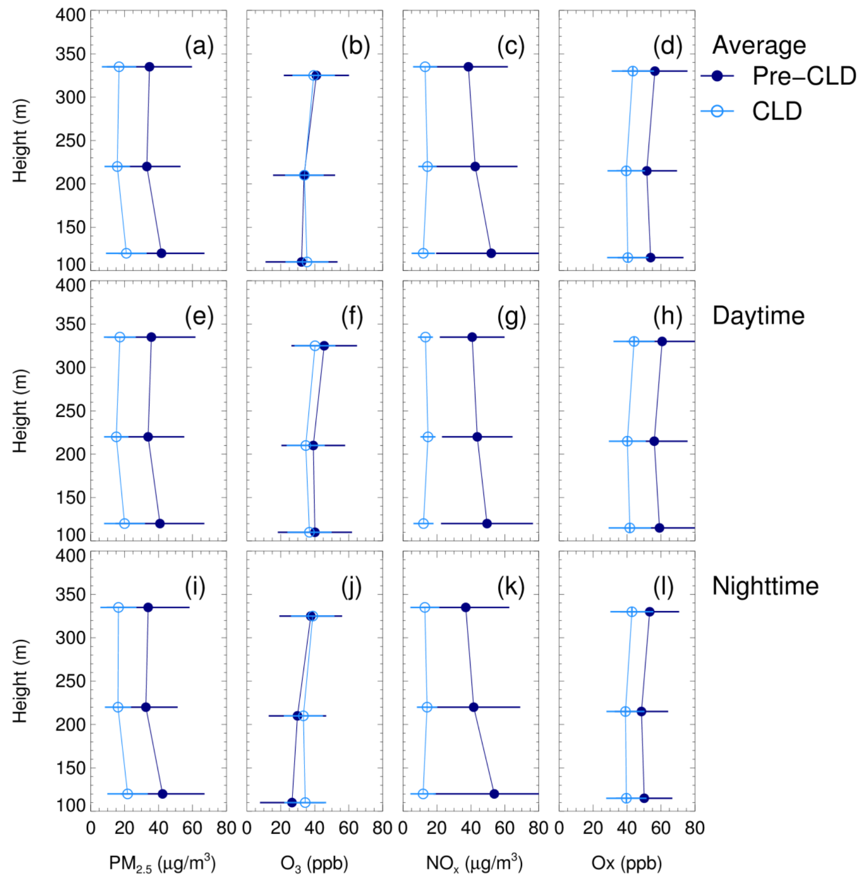

Fig. 7. Vertical distribution of three pollutants and Ox (= NO_2 + O_3) observed at the Shenzhen Meteorological Gradient Tower. Panel (a-d) show whole-day data; panel (d-h) show day-time data; and panel (i-l) show night-time data.

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As mentioned above, the O_3 concentrations increased monotonically with increasing altitude (Fig. 7b). Even during the lockdown, the average concentration of O_3 stayed high without showing any significant change. Completely different from the change of O_3, vehicular exhaust-gas emissions had plummeted to a very low level during the lockdown, which is clearly evidenced in Fig. 7c. This figure shows that the NO_x concentrations had decreased considerably at near-ground altitudes, especially at 120 m, where the concentration had decreased by over 75% compared with pre-lockdown levels. The persistence of high O_3 concentrations during the lockdown period proves the importance of VOCs for the air quality of this region once again. Actually, given the significant decrease in NO_x concentrations (as much as -78.2% in the current study), the concentrations of VOCs did not seem to have a same change as NO_x did. In recent studies, Qi et al (2021) reported that the decrease of VOCs in PRD during the lockdown is much less than that of NO_x, and Liu et al (2021) reported that formaldehyde (HCHO) abundance in the PRD area even slightly increased during the lockdown based on TROPOspheric Monitoring Instrument (TROPOMI) satellite observation, which indicate that VOCs were likely to play an even more important role in photochemical reactions during the lockdown period.

Figs. 7e–h and 7i–l displays the vertical distributions of pollutants and Ox during the day and night, respectively. The day-time and night-time distributions of $PM_{2.5}$, NO_x and Ox were not significantly different. By contrast, the vertical distribution of O_3 varied significantly between day and night. At all altitudes, the day-time O_3 concentrations were generally lower during the lockdown, whereas the night-time concentrations were higher. This paradoxical trend can be explained by the weakening of atmospheric chemical activity during the lockdown. Since the decrease in human activity during the lockdown also decreased primary pollutant emissions, the availability of precursors for photochemical O_3 generation was significantly lower, resulting in decreased day-time O_3 concentrations. During the night, the dark chemical reactions that consume O_3 also became less active during the lockdown, which resulted in significantly higher night-time O_3 concentrations at the near-surface atmosphere.

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These changes are consistent with the diurnal variations in O_3 (Fig. 5d).

3.4 Correlations at Different Altitudes

Fig. 8 depicts scatter plots and fit lines of O_3 versus $PM_{2.5}$ at each level of the SZMGT, before and during the lockdown.

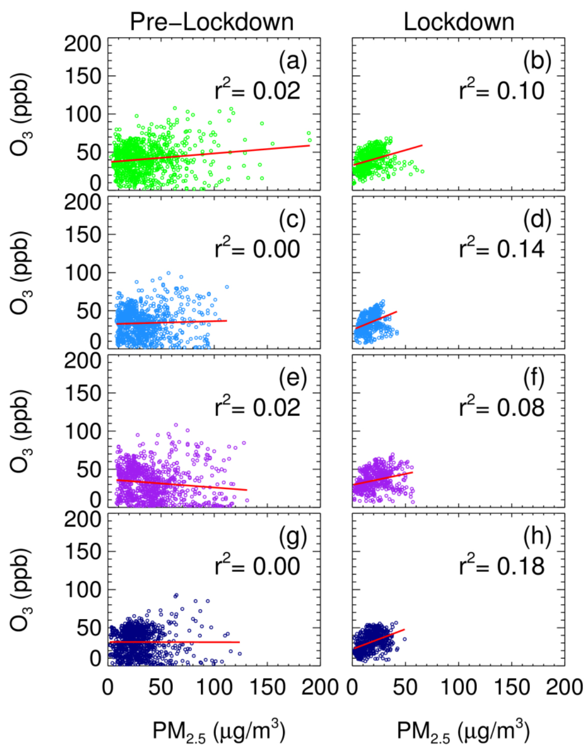

Fig. 8. Scatter plots of the $PM_{2.5}$ and O_3 concentrations at different heights of the meteorological tower before and during the lockdown: (a) and (b) are for ground level; (c) and (d) are for low level; (e) and (f) are for middle level; (g) and (h) are for high level. The fit lines of the plots were produced following the instruction of Cantrell (2008).

Prior to the lockdown, the correlation between the O_3 and $PM_{2.5}$ concentrations were weak, with none of the correlation coefficients (*R*) passing the significance test. When performing the correlation significance test for two

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variables, namely x and y, which means two different pollutants, the Pearson correlation coefficient *R* was calculated. Compare *R* to the appropriate critical value corresponding to the N-2 value in a standard table, where N is size of the sample set of (x, y) pairs. If the absolute value of R is greater than the critical value, the correlation between the two variables is significant. During the lockdown, the correlation between $PM_{2.5}$ and O_3 became significantly stronger, with the R values for the 0, 120, 220, and 335 m scatter plots all being significant at the 0.1 level. It may be inferred that prior to the lockdown, $PM_{2.5}$ and O_3 did not have related sources. However, during the lockdown, both were likely to have a similar source. In the PRD region, VOCs contribute significantly to the formation of fine particles (Liu et al., 2008; Zheng et al., 2009), especially secondary organic aerosols (Huang et al., 2006; Chang et al., 2019; Zhang et al., 2019). Although the advent of the COVID-19 pandemic did result in reductions in the concentrations of NO_x, SO_2, and other primary pollutants, the VOCs emissions might not change as dramatically as NO_x (Liu et al., 2021), which provided important precursors for both O_3 and the secondary organic aerosols during the lockdown, and strengthened the correlation between the $PM_{2.5}$ and O_3 concentrations.

Li et al. (2020) analysed the correlation coefficients of O_3 and $PM_{2.5}$ at different heights of SZMGT in December 2017, and the conclusions were different from this study. In December 2017, the correlation coefficient of O_3 and $PM_{2.5}$ increased significantly with the increase of height. They pointed out that this is because $PM_{2.5}$ is also mainly generated by photochemical reaction at high altitudes, so it has a strong correlation with O_3. At lower heights, a considerable part of $PM_{2.5}$ is primary source and had nothing to do with photochemical reactions, so it had much weaker correlation with O_3. While in this study, the correlation between $PM_{2.5}$ and O_3 was weak at all heights in the pre-lockdown period. The reason leading to this is mainly because that Shenzhen had conducted a large number of pollution emission control strategies in the past two years, resulting in a significant decrease in the primary pollutants. As shown in Table 1, the average concentration of $PM_{2.5}$ in the whole surface layer during the pre-lockdown period had decreased by 18.1% compared with December 2017, while the average concentration of

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O_3 had decreased by 36.2%. The decrease of O_3 concentration in the surface layer was twice that of $PM_{2.5}$, while the primary aerosol like black carbon is not reduced, indicating that there were much fewer products of photochemical reaction and secondary aerosol formation, so that the correlation coefficient between O_3 and $PM_{2.5}$ concentration was no longer high even in the higher heights. However, during the lockdown, the average concentration of $PM_{2.5}$ decreased again because the primary emission was drastically compressed. In this process, $PM_{2.5}$ formed from the primary emission became to be insignificant, and the photochemical oxidation of VOCs became to be important sources of particulate matter again. Therefore, the correlation coefficients between O_3 and $PM_{2.5}$ became to be higher than those before the lockdown.

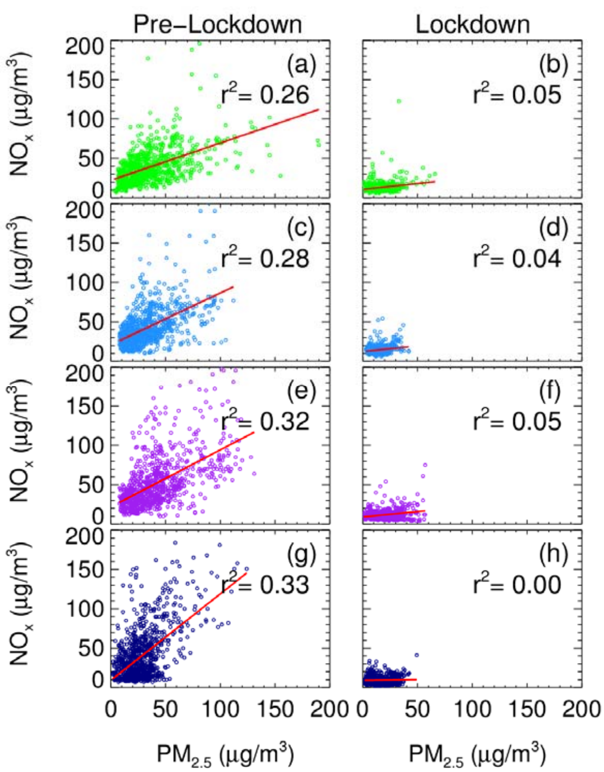

Fig. 9. Scatter plots of the $PM_{2.5}$ and NO_x concentrations at different heights of the meteorological tower before ad during the lockdown: (a) and (b) are for ground level; (c) and (d) are low level; (e) and (f) are for middle level; (g)

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and (h) are for high level.

Fig. 9 compares the correlation between the $PM_{2.5}$ and NO_x concentrations before and during the lockdown. The trend of the correlation between $PM_{2.5}$ and O_3 was the exact opposite of that between $PM_{2.5}$ and O_3; that is, it was strong before the lockdown (R = ~0.5 at all altitudes) but much weaker after (R = ~0.2 at all altitudes). Therefore, there may be significant differences between $PM_{2.5}$ sources before and during the lockdown. Owing to a lack of data, it was not possible to perform a composition analysis to determine why $PM_{2.5}$ was closely correlated with NO_x emissions prior to the lockdown but not during it. One possible explanation is that the primary emission of $PM_{2.5}$ in the PRD is a large part before the lockdown, since NOx can be treated as an indicator of anthropogenic emission, and primary emission of $PM_{2.5}$ decreased significantly during the lockdown. The other possible explanation is that the nitrate content of $PM_{2.5}$ in the PRD decreased significantly during the lockdown, given that it has been previously found that nitrate accounts for a large percentage of $PM_{2.5}$ before the year of 2020 (Yang et al., 2020).

Fig. 10 displays the correlation between the O_3 and NO_x concentrations before and during the lockdown. Prior to the pandemic, O_3 and NO_x were negatively correlated with each other owing to NO_x titration. The relationship between the O_3 and NO_x concentrations could be fitted with an exponential function. During the lockdown, the (negative) correlation between O_3 and NO_x weakened significantly, which means that at very low NO_x concentrations, variations in the concentration of this pollutant seemed to virtually have no obvious effect on the O_3 concentrations.

The comparison of scatter plots before and during the lockdown showed that $PM_{2.5}$ was poorly correlated to O_3 but closely correlated to NO_x before the lockdown, indicating that a large proportion of $PM_{2.5}$ might come from primary emissions or nitrate aerosol. While after the implementation of the lockdown, $PM_{2.5}$ became to be closely correlated to O_3, but not to NO_x, and O_3 formation cannot attribute to the local photochemistry, indicating that

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$PM_{2.5}$ during the lockdown might primarily be secondary pollutants (especially organic aerosols) generated from photochemical reactions.

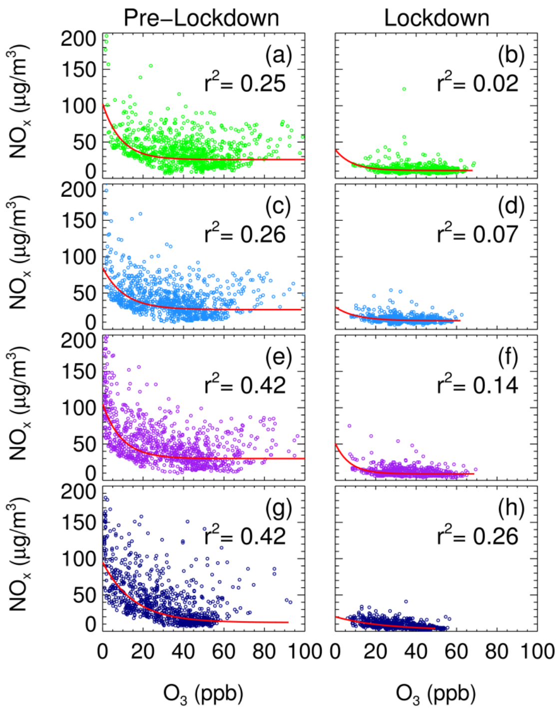

Fig. 10. Scatter plots of the O_3 and NO_x concentrations at different heights of the meteorological tower before and during the lockdown: (a) and (b) are for ground level; (c) and (d) are r low level; (e) and (f) re for middle level; (g) and (h) are for high level.

4 Conclusions and Implications

In this study, changes in the NO_x, O_3, and $PM_{2.5}$ concentrations over the PRD, mediated by the local COVID-19 pandemic lockdown measures, were investigated through the analysis of their vertical distribution before and during the lockdown, using data from the Shiyan Base and SZMGT. The conclusions of this study are as follows:

(1) The advent of the COVID-19 pandemic forced a dramatic decrease in human activity. This greatly reduced the emission of primary pollutants like NO_x, thus changing the chemical environment of the near-surface atmosphere. The concentration of $PM_{2.5}$ was also reduced significantly because of the decrease in precursor availability.

(2) The reduction in primary pollutant emissions during the COVID-19 pandemic lockdown significantly decreased MDA8O_3, while did not decrease the daily average concentration of O_3. The diurnal curves of O_3 concentration were changed by the lockdown, with the day-time concentrations being lower and the night-time ones being higher than the pre-pandemic concentrations at all levels of the SZMGT.

(3) The correlation between $PM_{2.5}$ and O_3 concentrations was insignificant before the lockdown but became significantly stronger after, to the point where the correlation coefficients between $PM_{2.5}$ and O_3 were significant at the 0.05 level, regardless of altitude. This indicates a strong correlation between $PM_{2.5}$ and O_3. By contrast, the correlation between $PM_{2.5}$ and NO_x was much weaker during the lockdown. Hence, the composition of $PM_{2.5}$ may have changed from being predominantly from primary emissions or nitrate aerosol before the lockdown to being predominantly a secondary organic aerosol thereafter. However, the validation of this hypothesis will require further investigations.

(4) Prior to the COVID-19 pandemic, the O_3 and NO_x concentrations were significantly negatively correlated with each other. This correlation virtually disappeared after the beginning of the pandemic. It may be concluded that at very low NO_x concentrations, variations in its concentration have almost no effect on the O_3 concentration.

Overall, the advent of COVID-19 has devastated economies and societies around the world. However, the dramatic reduction in human activity resulting from the lockdown measures has provided a unique opportunity for researchers to study the response of the atmospheric environment to human activities. The data indicate that the atmospheric chemical environment of the PRD has changed during the pandemic, leading the drastic change of

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pollutants concentrations. These results have a clear indication for pollution prevention policy. In the past, quite a few environmental policy studies doubted whether it was necessary to further reduce mobile emissions, because in some areas, decreasing NO_x led to an increase of O_3 concentration. While this study shows that the continuous reduction of NO_x emission can still reduce the peak value and $MDA8O_3$, although it will not further reduce the daily average value of O_3.

Competing interests.

The authors declare that they have no conflict of interest.

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References:

Brown, S. S., Thornton, J. A., Keene, W. C., Pszenny, A. A. P., Sive, B. C.,Dubé, W. P., Wagner, N. L., Young, C. J., Riedel, T. P., Roberts, J. M., VandenBoer, T. C., Bahreini, R., Ozturk, F., Middlebrook, A. M., Kim, S., Hubler, G., Wolfe, D.. Nitrogen, Aerosol Composition and Halogens on a Tall Tower (NACHTT): Overview of a Wintertime Air Chemistry Field Study in the Front Range Urban Corridor of Colorado. Journal of Geophysical Research: Atmospheres.118: 8067-8085. 2013.

Cantrell, C. A.. Technical note: Review of methods for linear least-squares fitting of data and application to atmospheric chemistry problems. Atmos. Chem. Phys., 8, 5477-5487. 2008.

Chakraborty, I., Maity, P.. COVID-19 outbreak: Migration, effects on society, global environment and prevention. Science of The Total Environment, 728: 138882. 2020.

Chang, D., Wang, Z., Guo, J., Li, T., Liang, Y., Kang, L., Xia, M., Wang, Y., Yu, C., Yun, H., Yue, D., Wang, T.. Characterization of organic aerosols and their precursors in southern China during a severe haze episode in january 2017. Science of Total Environment. 691, 101–111. 2019.

Gettelman, A., Chen, C.C., Bardeen, C.G.. The climate impact of COVID-19-induced contrail changes. Atmos. Chem. Phys., 21, 9405–9416. 2021.

Gualtieri, G., Brilli, L., Carotenuto, F., V Agnoli, C., Gioli, B.. Quantifying road traffic impact on air quality in urban areas: a covid19-induced lockdown analysis in italy. Environmental Pollution, 267, 115682. 2020.

Huang, X.F., Yu, J.Z., He, L.Y., Yuan, Z., Water-soluble organic carbon and oxalate in aerosols at a coastal urban site in China: size distribution characteristics, sources, and formation mechanisms. Journal of Geophysical Research. 111: D22212. 2006.

Kanniah, K. D., Zaman, N. A. F. K., Kaskaoutis, D., Latif, M. T.. COVID-19's impact on the atmospheric environment in the SoutheastAsia region. Science of The Total Environment, 736: 139658. 2020.

Kim, H.C., Kim, S., Cohen, M., Bae, C., Lee, D., Saylor, R., Bae, M., Kim, E., Kim, B.U., Yoon, J.H., Stein, A., Quantitative assessment of changes in surface particulate matter concentrations and precursor emissions over China during the COVID-19 pandemic and their implications for Chinese economic activity. Atmos. Chem. Phys., 21, 10065–10080. 2021.

Li, L., Chan, P.W., Wang, D.,Tan, M.. Rapid urbanization effect on local climate: intercomparison of climate trends in Shenzhen and Hong Kong, 1968-2013. Climate Research. 63, 145-155. 2015.

Li, L., Chan, P.W., Deng, T., Yang, H.L., Luo, H.Y., Xia, D., He, Y.Q.. Review of advances in urban climate study in the Guangdong-Hong Kong-Macau greater bay area, China. Atmospheric Research. 261,105759. 2021.

https://doi.org/10.5194/acp-2021-579
Preprint. Discussion started: 30 August 2021

Li, L., Lu, C., Chan, P. W., Zhang, X., Yang, H. L., Lan, Z. J., Zhang, W. H., Liu, Y. W., Pan, L., Zhang, L.. Tower observed vertical distribution of PM2.5, O3 and NOx in the pearl river delta. Atmospheric Environment, 220, 117083. 2020.

Liu, S., Liu, C., Hu, Q., Su, W., Yang, X., Lin, J., Zhang, C., Xing, C., Ji, X., Tan, W., Liu, H., Gao, M.. Distinct regimes of O_3 response to COVID-19 lockdown in China. Atmosphere. 12,184. 2021

Liu, Y., Shao, M., Lu, S., Chang, C.C., Wang, J.L., Fu, L.. Source apportionment of ambient volatile organic compounds in the Pearl River Delta, China: part II. Atmospheric Environment. 42, 6261–6274. 2008.

Meng, Z. Y., Ding, G. A., Xu, X. B., Xu, X. D., Yu, H. Q. Wang, S. F.. Vertical distributions of SO2 and NO2 in the lower atmosphere in Beijing urban areas, China. Sci. Total Environ. 390: 456-465. 2008.

Qi, J., Mo, Z., Yuan, B., Huang, S., Huangfu, Y., Wang, Z., Li, X., Yang, S., Wang, W., Zhao, Y., Wang, X., Wang, W., Liu, K., Shao, M.. 1.An observation approach in evaluation of ozone production to precursor changes during the COVID-19 lockdown. Atmospheric Environment. 262: 118618. 2021.

Rodríguez-Urrego, D., Rodríguez-Urrego, L.. Air quality during the covid-19: PM2.5 analysis in the 50 most polluted capital cities in the world. Environmental Pollution, 266: 115042. 2020.

Salma, I., Vörösmarty, M., Gyöngyösi, A.Z. Thén, W., Weidinger, T., What can we learn about urban air quality with regard to the first outbreak of the COVID-19 pandemic? A case study from central Europe. Atmos. Chem. Phys., 20, 15725–15742. 2020.

Srivastava, A.. COVID-19 and air pollution and meteorology-an intricate relationship: A review. Chemosphere, 263: 128297. 2021.

Sun, Y.Wang, Y., Zhang, C. Vertical Observations and Analysis of PM2.5, O3, and NOxat Beijing and Tianjin from Towers during Summer and Autumn 2006. Advances in Atmospheric Sciences. 27: 123-136. 2010.

Sun, Y., Song, T., Tang, G., Wang, Y. The vertical distribution of PM2.5 and boundary-layer structure during

https://doi.org/10.5194/acp-2021-579
Preprint. Discussion started: 30 August 2021

summer haze in Beijing. Atmospheric Environment. 74: 413-421. 2013.

Vo, T.D.H., Lin, C., Weng, C.E., Yuan, C.S., Lee, C.W., Hung, C.H., Bui, X.T., Lo, K.C., Lin, J.X.. Vertical stratification of volatile organic compounds and their photochemical product formation potential in an industrial urban area. Journal of Environmental Management. 217: 327–336. 2018.

Wang, C., Horby, P.W., Hayden, F.G., Gao, G.F.. A novel coronavirus outbreak ofglobal health concern. Lancet.395(10223):470-473. 2020.

Wang, S., Ma, Y., Wang, Z., Wang, L., Chi, X., Ding, A., Yao, M., Li, Y., Li, Q., Wu, M., Zhang, L., Xiao, Y., Zhang, Y., Mobile monitoring of urban air quality at high spatial resolution by low-cost sensors: impacts of COVID-19 pandemic lockdown. Atmos. Chem. Phys., 21, 7199–7215. 2021.

Wang, Q., Su, M., A preliminary assessment of the impact of COVID-19 onenvironmenteA case study of China.Science of The Total Environment. 138915. 2020.

Xing, J., Li, S., Jiang, Y., Wang, S., Ding, D., Dong, Z., Zhu, Y., Hao, J.. Quantifying the emission changes and associated air quality impacts during the COVID-19 pandemic on the North China Plain: a response modeling study. Atmos. Chem. Phys., 20, 14347–14359. 2020.

Yang, H.L., Zhang, Y., Li, L., Chan, P.W., Lu, C., Zhang, L., Characteristics of aerosol pollution under different visibility conditions in winter in a coastal mega-city in China. Journal Tropical Meteorology, 26(2), 231-238. 2020.

Zhang, Y.Q., Chen, D.H., Ding, X., Li, J., Zhang, T., Wang, J.Q., Cheng, Q., Jiang, H., Song, W., Ou, Y.B., Ye, P.L., Zhang, P.L., Zhang, G., Wang, X.M.. Impact of anthropogenic emissions on biogenic secondary organic aerosol: observation in the Pearl River Delta, southern China. Atmos. Chem. Phys., 19, 14403–14415. 2019.

Zhang, L., Li, L., Chan, P. W.,Al., E.. Why the number of haze days in Shenzhen, China has reduced since 2005: From a perspective of industrial structure. MAUSAM, 1: 45-54. 2018.

https://doi.org/10.5194/acp-2021-579
Preprint. Discussion started: 30 August 2021

Atmospheric Chemistry and Physics Discussions

Zheng, J., Shao, M., Che, W., Zhang, L., Zhong, L., Zhang, Y., Streets, D., Speciated VOC emission inventory and spatial patterns of ozone formation potential in the Pearl River Delta, China. Environmental Science & Technology. 43: 8580–8586. 2009.

Xu, X., Lin, W., Xu, W., Jin, J., Wang, Y., Zhang, G., Zhang, X., Ma, Z., Dong, Y., Ma, Q., Yu, D., Li, Z., Wang, D., Zhao, H.. Long-term changes of regional ozone in China: implications for human health and ecosystem impacts. Elem Sci Anth, 8: 13. 2020.