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Responses of decline in air pollution and recovery associated with COVID-19 lockdown in the Pearl River Delta

Siyu Wang a, Yanli Zhang b, Jinlong Ma a, Shengqiang Zhu a, Juanyong Shen c, Peng Wang d,⁎, Hongliang Zhang a,⁎⁎

a Department of Environmental Science and Engineering, Fudan University, Shanghai 200438, China
b State Key Laboratory of Organic Geochemistry and Guangdong Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China
c School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
d Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hong Kong 99907, China
e Institute of Eco-Chongming (IEC), Shanghai 200062, China

HIGHLIGHTS
• In the PRD, PM2.5 reduced and then slightly increased from Period I to III.
• O3 had no obvious change from Period I to II and increased in Period III.
• Emission reduction in Period II made the decrease of pollutants.
• Higher temperature in Period III promoted the formation of secondary pollutants.

ABSTRACT
The Guangdong government implemented lockdown measures on January 23, 2020, to ease the spread of the coronavirus disease 2019 (COVID-19). These measures prohibit a series of human activities and lead to a great reduction in anthropogenic emissions. Starting on February 20, all companies resumed work and production, and emissions gradually recovered. To investigate the response of air pollutants in the Pearl River Delta (PRD) to the emission reduction and recovery related to COVID-19 lockdown, we used the Community Multi-scale Air Quality (CMAQ) model to estimate the changes in air pollutants, including three periods: Period I (January 10 to January 22, 2020), Period II (January 23 to February 19, 2020), Period III (February 20 to March 9, 2020). During Period II, under the concurrent influence of emissions and meteorology, air quality improved significantly with PM2.5, NO2, and SO2 decreased by 52%, 67%, and 25%, respectively. O3 had no obvious changes in most cities, which mainly due to the synergetic effects of emissions and meteorology. In Period III, with the recovery of emissions and the changes in meteorology, the increase of...
1. Introduction

With the rapid economic development in past decades, China is suffering from severe air pollution, adverse health outcomes, huge ecological damage, and economic loss (Giani et al., 2020a; Han et al., 2016; Hu et al., 2016). As one of the fastest-growing economic regions in China, the Pearl River Delta (PRD) region is suffering from severe air pollution events (Hu et al., 2012; Wu et al., 2020; Zhang et al., 2013; X. Zhang et al., 2012; Zhou et al., 2014). Ou et al. (2016) reported that the maximum 1 h ozone (O3) can be up to 150–200 ppb in the summer and fall in the PRD region. To mitigate the severe pollution, Guangdong Province first implemented the "Pearl River Delta Clean Air Action Plan" in 2010 (Yang et al., 2020) and issued the “Three-Year Action Plan to Win the Blue Sky Defense War” in 2018. With the implementation of these plans, the air quality in the PRD has improved. Observations data from the China National Environmental Monitoring Center (CNEMC) show a 30%–50% decrease in annual average concentration of fine particulate matter (PM2.5, particles with aerodynamic diameter ≤ 2.5 μm) across China over the 2013–2018 period, and the mean concentration in the PRD decreased from 47 μg/m³ in 2013 to 31 μg/m³ in 2018 (Zhai et al., 2019). Zhang and Li (2017) also found the mean concentration of PM2.5 in PRD decreased from 120 μg/m³ at the highest peak to 34 μg/m³ in 2015. However, rising trends of O3 exist in recent years (Hou et al., 2018; Wang et al., 2019; Wang et al., 2017), increasing challenges for the PRD to meet the WHO Air Quality Guidelines.

With the outbreak of new coronavirus disease 2019 (COVID-19), a series of measures have been taken in China to control its rapid spread (Tian et al., 2020). Wuhan, as the starting point of the outbreak, announced to be shut down on January 23 (Enitan et al., 2020) and the Guangzhou government declared the lockdown on the same day (Pei et al., 2020). Then, most traffic was prohibited, and almost all outdoor activities were stopped (C. Wang et al., 2020). Due to these restrictions, anthropogenic emissions are believed to have been drastically decreased. National Aeronautics and Space Administration (NASA) released satellite images showed that nitrogen dioxide (NO2) levels have decreased significantly over China at this time (Muhammad et al., 2020; Wang and Su, 2020). In the PRD, nitrogen oxides (NOx) and PM2.5 concentrations decreased significantly, but O3 concentration had no obvious change (Huang and Sun, 2020; P. Wang et al., 2020). For instance, a mean 46% reduction of NO2 was found in Guangzhou (megacity in the PRD) during the lockdown, however, a slight decrease of O3 was observed at the same time (Pei et al., 2020) (Fig. S1). This may have been a result of differences in meteorology conditions involving the formation of air pollution (Liu et al., 2020; Yang et al., 2018). Ma et al. (2020) detected a significant positive correlation between O3 and temperature (T) that T was the main driving factor for O3 concentration. The PRD is affected by a typical subtropical climate and Asian monsoons and tropical cyclones, which may reduce the benefits of emission reductions.

After the effective control of COVID-19 spread in February, most areas started economic recovery and anthropogenic emissions gradually increase to a normal level. The enterprises in the PRD have resumed to work on 20, February based on the notice issued by the Guangdong government. In the meantime, the weather in the PRD changed from cold winter to warm spring. This provides a valuable opportunity to assess the impact of reduction and recovery of anthropogenic emissions as well as meteorological conditions on air pollutants in a short period. Cui et al. (2020) reported that the PM2.5 and its major components decreased during the lockdown period, and increased after the control period as the work resumed at a rural site between Beijing and Tianjin. However, studies that focused on the effects of emissions and meteorology on air quality in the PRD for the entire period of shutdown and recovery are limited (Giani et al., 2020b; He et al., 2020).

In this study, the Community Multiscale Air Quality (CMAQ) model was used to simulate air pollutants before, during, and after the COVID-19 outbreak in the PRD. It aims to compare pollutant levels in these three periods and assess the impact of anthropogenic emissions reduction caused by the lockdown and discuss the role of meteorology in air quality changes. This research would provide an important basis for designing effective control strategies for further air quality improvement in the PRD.

2. Methods

2.1. Model application

In this study, the CMAQ version 5.0.2 was conducted with nested domains of 36 km and 12 km in the PRD from January 5 to March 9, 2020. The 36 km domain covers China and surrounding countries and the 12 km domain covers the PRD and surrounding provinces (Fig. S1). The updated SAPRC-11 chemical mechanism was applied for better simulations (Carter and Heo, 2013; Ying et al., 2015). The meteorological inputs were generated using the Weather Research & Forecasting (WRF) model version 3.6.1 driven by FNL (Final) Operational Global Analysis data from the National Center for Environmental Prediction (NCEP) (NCEP, 2000; Qiao et al., 2019). The Multi-resolution Emission Inventory for China (MEIC) of 2016 (http://www.meicmodel.org) provides anthropogenic emissions from different sources including power, industry, residential, transportation, and agriculture. Biogenic emissions were generated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2.1 (Guenther et al., 2012).

2.2. Emission scenarios

The simulation covers three periods from January 10 to March 9, January 23 was the starting point of the pandemic period and February 20 was the time when all companies can resume work and production. Therefore, January 5 to 22 was Period I before the pandemic, Period II during the pandemic was from January 23 to February 19, and February 20 to March 9 was Period III after the pandemic (Table S1). Two simulation scenarios were performed (Table 1). Period I and Period III used original anthropogenic emissions (Case 1) while Period II applied secondary components was faster than that of primary PM2.5 (PM), which indicated that changes in PPM concentration were more sensitive to emissions reduction. O3 concentration increased as emission and temperature rising. Our findings elucidate that more effective emission control strategies should be implemented in PRD to alleviate the increasingly serious pollution situation.

Table 1: Configuration of simulation periods with emission scaling factors.

| Period | CO | NO2 | SO2 | VOC | PM2.5 | Province |
|--------|----|-----|-----|-----|-------|----------|
| I      | No change |
| II     | 38% | 50% | 33% | 46% | 27%   | Guangdong |
| II     | 24% | 50% | 28% | 39% | 17%   | Guangxi |
| II     | 24% | 39% | 25% | 30% | 22%   | Guizhou |
| II     | 24% | 44% | 25% | 36% | 14%   | Hainan |
| II     | 24% | 51% | 25% | 36% | 20%   | Hunan |
| II     | 24% | 53% | 21% | 41% | 19%   | Jiangxi |
| II     | 29% | 51% | 30% | 42% | 19%   | Fujian |
reduced emissions (Case 2). The emission reduction ratios of carbon monoxide (CO), NOx, sulfur dioxide (SO2), the volatile organic compound (VOC), and PM2.5 in the 12 km domain in Period II were based on Huang et al. (2020a). Table 1 lists the specific factors used in Period II simulation. Huang et al. (2020b) updated China’s emissions data to Jan and Feb 2020 based on dynamic economic and industrial activity levels to estimate emission reductions due to COVID-19 lockdown. The emissions of NOx decreased the most as the largest source, transportation, was limited the most during the pandemic (Che et al., 2011).

In the PRD, we mainly studied four cities, including megacities as Guangzhou, and Shenzhen, and developing cities as Jiangmen, and Zhaoqing (Fig. S1). The site information of the four cities was shown in Table S2. The different locations and development levels of these cities are capable to provide a more comprehensive understanding of the impacts of emissions and meteorological conditions on air quality.

3. Results and discussion

3.1. Model validation

Reliable meteorological modeling is essential to ensure the accuracy of air quality predictions. Mean observation (OBS), mean prediction (PRE), mean bias (MB), gross error (GE), and root mean square error (RMSE) of major variables between WRF simulation and available observations within the grid cell are shown in Table S3. Meteorological observations including precipitation, wind speed (WS), and wind direction (WD) at 10 m, and temperature (T) and relative humidity (RH) at 2 m above the ground level were obtained from the National Climate Data Center (NCDC). The benchmarks suggested by Emery et al. (2001) were also included to judge model performance. T2 was slightly beyond the benchmark with GE of 2.02 in January, while other values were with the benchmarks. GE values of WS met the benchmark in both months, while MB and RMSE were beyond the benchmarks. WD and RH predictions were acceptable within slightly underestimation of WD and overestimation of RH. Although not perfectly within the benchmarks, the WRF model predictions in this study are comparable to other studies applying WRF in China (Hu et al., 2015; H. Zhang et al., 2012) and suitable for driving the CMAQ model.

Table S4 shows the model performance statistics of key pollutants, including 1 h peak O3 (O3-1h), CO, NOx, SO2, PM2.5 and inhalable particulate matter (PM10) in Case 2 during the lockdown period. Observations were obtained from the China National Environmental Monitoring Center (http://www.mee.gov.cn/hjzl/dqhj/) with 90 stations in the PRD (Zhang et al., 2020). O3-1h and PM2.5 were well predicted as the statistics all met the criteria. MFB and MFE for PM2.5 were — 0.04 and 0.7, which met the criteria limits of ±0.6 and 0.75 claimed by EPA (2007). NOx was underestimated by the MNB of — 0.09 and SO2 was overestimated by the MNB of 0.76, which due to the emission uncertainties.

From the time series, the model was able to reproduce the changing trends of PM2.5 and O3 in the selected cities (Figs. 1, 2). The predictions of PM2.5 concentrations were well consistent with the observations, while in Guangzhou and Jiangmen were slightly overpredicted in Period I. In Period I and Period III, the predicted O3 in all cities agreed well with the observations, and the variation trends were well captured. In most cities, O3 was still over-estimated during Period II although the
emissions have been reduced to reproduce the observed concentrations, which was likely due to the uncertainties in the emission adjustment factors we used (Liu et al., 2020; Xing et al., 2020). Generally, the WRF/CMAQ modeling system reproduced well the PM2.5 and O3 concentrations in most cities and the model performance was similar with studies in the PRD and other regions in China (Deng et al., 2018; Li et al., 2019; Tao et al., 2014).

3.2. Changes of air quality in three Periods

In order to quantify the changes in the concentration of pollutants in the cities of PRD, we calculated the observed average of these four cities in the three periods (Table 2). It can be clearly seen that emission reduction has a positive effect on reducing PM2.5 and NO2 concentrations during Period II. An average of 9.18 μg/m³ decrease in PM2.5 was found in all cities and in Shenzhen, the reduction of PM2.5 was up to 11.32 μg/m³. In Period III, the concentrations of PM2.5 in Guangzhou and Zhaoqing began to rise (1.77 and 5.44 μg/m³, respectively), however, their levels did not comparable to that in Period I. NO2, one of the major precursors to nitrate (NO3⁻) (major components in PM2.5) (Xie et al., 2015), had a dramatic reduction (at least 6.32 ppb) in all cities, with the most decreasing found in Jiangmen (up to 59%) during Period II. Then the concentration of NO2 immediately increased in all cities in Period III, mainly due to the increase in vehicle exhaust emissions and industrial fuel combustion. The same trends of NO2 were also reported in other studies in east China (R. Zhang et al., 2020). Also, the similar variation trends were found in SO2 from Period I to Period III. Simultaneously, a slight reduction of MDA8 O3 was observed in Shenzhen and Jiangmen in Period II. Rising O3 trends were found in all cities in Period III.

Table S5 shows the observed meteorological in these four cities in three Periods. The average temperature had a trend that first decreasing and then rising from Period I to Period III, which may explain the changes in O3 in Shenzhen and Jiangmen. The temperature plays important role in photochemical reactions, and higher temperatures are conducive to the production of O3 (Campra, 2018). However, for the entire

Table 2

| City      | Period I | Period II | Period III |
|-----------|----------|-----------|------------|
| Guangzhou | MDA8 O₃  | 30.46     | 30.91      | 42.22      |
|           | PM₂.₅   | 27.84     | 21.11      | 22.88      |
|           | NO₂      | 20.56     | 9.90       | 17.75      |
|           | SO₂      | 2.13      | 1.72       | 1.99       |
| Shenzhen  | MDA8 O₃  | 37.88     | 32.52      | 37.76      |
|           | PM₂.₅   | 30.28     | 18.96      | 18.96      |
|           | NO₂      | 13.04     | 6.72       | 10.32      |
|           | SO₂      | 1.92      | 1.75       | 1.80       |
| Jiangmen  | MDA8 O₃  | 34.43     | 32.83      | 44.73      |
|           | PM₂.₅   | 28.82     | 21.26      | 19.17      |
|           | NO₂      | 18.46     | 7.51       | 11.02      |
|           | SO₂      | 2.10      | 1.66       | 1.90       |
| Zhaoqing  | MDA8 O₃  | 25.32     | 29.08      | 39.33      |
|           | PM₂.₅   | 32.29     | 21.19      | 26.63      |
|           | NO₂      | 15.15     | 6.48       | 11.82      |
|           | SO₂      | 1.92      | 1.92       | 2.62       |
Guangdong Province, the ozone concentration increased, mainly because of the inverse correlation between PM$_{2.5}$ and O$_3$, which was attributed to the photochemical effect of aerosol radiation on the formation of O$_3$ (Le et al., 2020). The averaged WS had the opposite trend of temperature, first rising and then declining. The increase in WS is beneficial to the diffusion of pollutants (Gui et al., 2019), resulting in a decrease in PM$_{2.5}$ concentrations in Periods II. In four cities, the simulated PM$_{2.5}$ concentrations can reach up to 120 μg/m$^3$ in Period I and the maximum concentration in Period II did not exceed 80 μg/m$^3$ (Fig. 1). The decreasing trend of O$_3$ was not very obvious from Period I to Period II in the four cities (Fig. 2). But there was a clear upward in Period III, the highest concentration exceeded 100 ppb.

The average observed concentrations of MDA8 O$_3$, PM$_{2.5}$, NO$_2$, and SO$_2$ in the three periods corresponding to 2019 were also calculated, as well as the meteorological conditions (Tables S6, S7). Compared with 2019, the concentration of PM$_{2.5}$, NO$_2$, and SO$_2$ decreased in Period I and Period II in 2020, which may attribute to the emission reduction policies in recent years. In Period I, compared to levels in 2019, PM$_{2.5}$ concentrations in 2020 decreased by 47%, 21%, 41% and 31% in Guangzhou, Shenzhen, Jiangmen, and Zhaoqing, respectively. The decline was corresponding to the reduction in WS. In Period II, relative to 2019, the decrease of PM$_{2.5}$ was average 11.77 μg/m$^3$ in four cities. Giani et al. (2020b) also found the comparable change level with the average concentration of PM$_{2.5}$ in 2016–2019 (34.73 μg/m$^3$) and 2020 (22.67 μg/m$^3$) during the lockdown period. NO$_2$ and SO$_2$ also showed an obvious decrease in 2020. In Period II, the emission reduction of NO$_2$ in 2020 (average 54%) was about 1.5 times larger than that in 2019 (average 37%), compared with Period I. We may attribute the additional reduction to the lockdown.

Throughout the simulation period, the concentration of PM$_{2.5}$ presents a tendency to decrease first and then a slight increase in the PRD (Fig. 3). Higher PM$_{2.5}$ concentrations are found in the central part of the PRD, with a peak value of 50 μg/m$^3$ during Period I. The reason is the central part is mostly the cities with higher emissions (Fig. S2). In the PRD, the concentration of PM$_{2.5}$ decreased by an average of about 40% in Period II and gradually increased in Period III. This showed that the reduction in emissions caused by COVID-19 has indeed led to a reduction in PM$_{2.5}$, which was also reported in other studies (Chauhan and Singh, 2020; Chu et al., 2020). In contrast, the concentration rebounded after the resumption of work. Considering components of PM$_{2.5}$, the secondary inorganic aerosol (SIA, including NO$_3^-$, sulfate (SO$_4^{2-}$) and ammonium (NH$_4^+$)) accounts for the largest proportion in the PM$_{2.5}$ and declined significantly from Period I to Period II. In Guangzhou, the NO$_3^-$ even decreased by 50% during Period II (Fig. S3), which mainly resulted from the reduction of NO$_2$ emissions (Ding et al., 2017) from the on-road transportation and industry sectors. In Period III, the concentration PM$_{2.5}$ and its components increased in the more developed cities such as Guangzhou and Shenzhen, especially the secondary pollutants (SIA and secondary organic aerosol (SOA)). However, the lower levels of primary PM$_{2.5}$ (PPM) were found in the same time period. In particular, NOA decreased by 43% in Period II and 54% in Period III in Jiangmen as shown in Fig. 4. Overall, the secondary components recovered faster than the primary PM$_{2.5}$, indicating that the concentration changes of PPM are more sensitive to emission reductions. Similar results of PM$_{2.5}$ were also reported in other regions such as Wuhan during the COVID-19 lockdown periods (Zheng et al., 2020). We also compared the changes of NO$_2$ and SO$_2$ in the PRD from Period I to Period III (Fig. S4). The NO$_2$ decreases more than 60% from Period I to Period II, and then recovered by about 40% in the Period III, which was mainly due to changes in traffic-related pollution emissions (Chen et al., 2020). The concentration change trend of SO$_2$ in the three periods was consistent with that of NO$_2$, but the decrease in the Period II was not as obvious as that of NO$_2$. The NO$_2$ and SO$_2$ are major precursors of SIA (Xie et al., 2015), which have an important impact on the change of PM$_{2.5}$ concentrations from Period I to Period III.

Researches on PM$_{2.5}$ showed different change levels in various regions during the COVID-19 pandemic compared to the PRD (Giani et al., 2020b). Silver et al. (2020) concluded that the decrease in PM$_{2.5}$ during the COVID-19 lockdown was ranged from −17.2% in the PRD to −2.0% in the North China Plain (NCP), which was due to different weather conditions. During the lockdown, changes in meteorological conditions also have an important effect on PM$_{2.5}$. In this study, the reduced PM$_{2.5}$ in Period II was partially attributed to the high WS (Fig. 5), which facilitated the diffusion of PM$_{2.5}$. In contrast, the increased RH after the resumption of work (Period III) promoted the formation of PM$_{2.5}$ due to its positive role of aqueous-phase aerosol chemistry (Song et al., 2019; Zhai et al., 2019).

The maximum daily 8-hour average ozone (MDA8 O$_3$) concentration has decreased in most part areas of PRD in Period II and slightly increased in Period III (Fig. 3). In the central of PRD, O$_3$ has slightly increased in Period II. The reason was that the reduction of NO$_2$ emissions (Fig. S4) leads to an increase in the O$_3$ concentration in these the VOC sensitive area (Li et al., 2013). Unlike the situation of PRD, studies in the Yangtze River Delta (YRD) and NCP found the obvious enhancements of O$_3$ during Period II due to the reduction in the NO$_x$ titration effect and increase in atmospheric oxidation capacity (AOC) (Huang et al., 2020a) (Silver et al., 2020). Although AOC in the PRD also increased in these cities (Fig. S5), the impact of emissions reduction reduced the
Fig. 4. Predicted major components of PM$_{2.5}$ in four cities, including Guangzhou, Shenzhen, Jiangmen, Zhaoqing. Three different colors represent three periods. NO$_3^-$ is nitrate, SO$_4^{2-}$ is sulfate, NH$_4^+$ is ammonium, EC is elemental carbon, POA is primary organic aerosol, SOA is secondary organic aerosol.

Fig. 5. Regional variation of relative humidity (RH), temperature (T), wind speed (WS) and planetary boundary layer height (PBL) in three Periods.
impact of AOC on O₃ concentration. In Period III, the general increase in O₃ concentration was partly due to the increase in the emission of its precursors and rise in temperature (Gong and Liao, 2019; Gu et al., 2020; Porter and Heald, 2019).

3.3. Roles of emission reductions

In order to explore the impact of the reduction in anthropogenic emissions due to the COVID-19 control measures on air quality (excluding the influence of meteorological conditions), we compared four criteria air pollutants of two cases (Case 1 and Case 2) in Period II and III, respectively (Figs. 6 and S6).

Fig. 6 shows the regional change in the predicted concentration of MDA8 O₃, PM₂.₅, NO₂, and SO₂ in two cases during the lockdown and the difference between Case 1 and Case 2. In the whole PRD, PM₂.₅, NO₂, and SO₂ all decreased in Case 2 compared with Case 1 during Period II while O₃ increased in the central area. The PM₂.₅ decreased most by 7 μg/m³ in the center of PRD, where have the most intensive population density and the fastest industrial development in the PRD, indicating that emission reduction is the major contributor to the reduction of PM₂.₅. From Fig. S7, PPM emissions in the PRD decreased prominently in Period II, leading to a 28% decrease in PM₂.₅. Also, the concentrations of NO₂ and SO₂ decreased significantly (average 20%). However, the MDA8 O₃ (~4 ppb) in the PRD increased with the NOx emission reductions. This is likely due to the fact that most areas of PRD were sensitive to volatile organic compounds (VOCs) (Li et al., 2013), so the increase in O₃ can be attributed to the reduction in NOx emissions. VOC was also reduced and the reduction ratio (46%) is less than NOx (50%) (Fig. S8), which drove the O₃ still rise. This demonstrates that it is necessary to consider the coordinated emission reduction ratio of VOC and NOx, otherwise, it would aggravate O₃ pollution in the PRD (Zhong et al., 2013).

Fig. S6 shows changes of these pollutants from Case 1 and Case 2 during Period III to investigate the impacts of emissions control policies on air quality in the recovery time. Similar to Period II. The concentrations of PM₂.₅, NO₂, and SO₂ have been decreased to varying degrees with lower emissions. However, different O₃ variations were found during Period III from Period II, which decreased in all cities except for the west Shenzhen. This illustrates that if emissions control policy is implemented till Period III, the pollution situation including O₃ will be further improved.

3.4. Role of meteorology

To investigate the roles of meteorological conditions in the concentration of pollutants, the meteorological changes in the PRD its major cities were compared from Period I to Period III (Figs. 5 and S9).

During Period II, RH and temperature decreased slightly, which averagely 2% and 4%, respectively. It is clear that RH in the PRD was lower than the surrounding cities and the T was relatively higher. WS (at 10 m above the ground level) increased by 0.5 m/s on average in Period II, which are essential for pollutant dispersion and transport (Gui et al., 2019). Therefore, in Period II, a large part of the reduction in PM₂.₅ concentrations was due to the increase in WS, except for the reduction in emissions. At the same time, the average PBL also increased, which can also accelerate the diffusion of pollutants, thereby improving the pollution situation.
In Period III, both RH and temperature increased significantly, and the change rate did not differ greatly in regional distributions. WS had a decrease of about 5%. These changes in meteorological conditions tend to enhance the concentration of pollutants. In this period, the variation of PM$_2.5$ concentration was 6 g/m$^3$ under the influence of emissions, while PM$_{2.5}$ increased averagely 2 g/m$^3$ from Period II to Period III, which explained that meteorology offset part of the impact of emission restoration on the concentration. By contrast, PBL continued to rise, and the rate of change (16%) in Jiangmen exceeded other meteorological conditions, which resulted in the declined concentration of PM$_{2.5}$ in Jiangmen during Period III. In summary, the meteorological conditions induce important impacts on the concentration of pollutants.

4. Conclusion

In the PRD, decreased PM$_{2.5}$ and NO$_2$ were observed in Period II compared with Period I. During Period III, pollution in most cities began to increase gradually. O$_3$ had no obvious changes from Period I to Period II due to the decline of its precursor NO$_x$ that offsets the higher AOC. The increase in O$_3$ during Period III is attributed the recovery of emissions and the rise in temperature in Period III. The PM$_{2.5}$ concentrations were higher in the central part of the PRD, up to 50 g/m$^3$ in Period I, and decreased by 50% on average in Period II. In Period III, the secondary components of PM$_{2.5}$ began to recover, but the primary PM$_{2.5}$ was still declining, indicating that emission reduction has a greater impact on primary pollutants. The O$_3$ concentration in the center was lower than that in the surrounding cities, and MDA8 O$_3$ in southern Guangzhou slightly increased during Period II.

The PM$_{2.5}$, NO$_2$, and SO$_2$ are all reduced due to the reduction of emissions in Case 2 compared with Case 1, while O$_3$ increases by about 4 ppb in Period II. In the center of the PRD with the highest population density and the fastest industrial development, the largest decline in PM$_{2.5}$ was 7 g/m$^3$, which indicated that the reduction in emissions is one of the main factors causing the decline in PM$_{2.5}$. In addition, Case 2 showed that if emissions reduction continues, secondary pollutants including O$_3$ would continue to decline in Period III. At the same time, meteorological influence also played an important role in the air quality from Period I to Period III. The increase in average WS and PBL in Period II was conducive to the diffusion of pollutants, while the increase in temperature and decrease in WS in Period III will promote the accumulation of pollution.

Our results show that the emission control measures adopted by the lockdown have improved the air pollution situation for a period of time, and when the emissions increase, the pollution will gradually recover under the common influence of meteorology. This indicates that PRD should implement more stringent and effective control policies, and pay more attention to secondary pollutants such as O$_3$.

CRediT authorship contribution statement

Siyu Wang: Methodology, Simulation, Data collection, Visualization, Writing-original draft. Yanli Zhang: Data collection, Writing reviewing and editing. Jinlong Ma: Methodology, Visualization. Shengqiang Zhu: Methodology, Data collection. Juanyong Shen: Data collection. Peng Wang: Methodology, Writing-reviewing and editing. Hongliang Zhang: Conceptualization, Methodology, Writing reviewing and editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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