Driving Forces of Changes in Air Quality during the COVID-19 Lockdown Period in the Yangtze River Delta Region, China

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ABSTRACT: During the COVID-19 lockdown period (from January 23 to February 29, 2020), ambient PM$_{2.5}$ concentrations in the Yangtze River Delta (YRD) region were observed to be much lower, while the maximum daily 8 h average (MDA8) O$_3$ concentrations became much higher compared to those before the lockdown (from January 1 to 22, 2020). Here, we show that emission reduction is the major driving force for the PM$_{2.5}$ change, contributing to a PM$_{2.5}$ decrease by 37% to 55% in the four YRD major cities (i.e., Shanghai, Hangzhou, Nanjing, and Hefei), but the MDA8 O$_3$ increase is driven by both emission reduction (29%–52%) and variation in meteorological conditions (17%–49%). Among all pollutants, reduction in emissions mainly of primary PM contributes to a PM$_{2.5}$ decrease by 28% to 46%, and NOx emission reduction contributes 7% to 10%. Although NOx emission reduction dominates the MDA8 O$_3$ increase (38%–59%), volatile organic compounds (VOCs) emission reduction lead to a 5% to 9% MDA8 O$_3$ decrease. Increased O$_3$ promotes secondary aerosol formation and partially offsets the decrease of PM$_{2.5}$ caused by the primary PM emission reductions. The results demonstrate that more coordinated air pollution control strategies are needed in YRD.

INTRODUCTION

The 2019 novel coronavirus (COVID-19) broke out first in Wuhan, China, in late December of 2019.1–3 To prevent the spread of COVID-19, China had quickly taken a series of countermeasures. On January 23, 2020, the national public health response was raised to the highest state of emergency, and at the same time, travel between cities was strictly prohibited (lockdown). During the lockdown period, except for the regular operation of supermarkets, clinics, and pharmacies that provide livelihood supplies, traveling was largely restricted, public transportation was banned across the country, large shopping centers and entertainment venues closed, many business and industries stopped, and schools also postponed starting.4,5 The lockdown played a very positive role in preventing the spread of the virus.6 As an unexpected benefit, air pollutant emissions from transportation and some industries were dramatically reduced under the strict controls, which provides a unique opportunity to investigate the effects of significant reductions in anthropogenic emissions on air quality. A few studies have investigated the air quality changes during the COVID-19 outbreak in China and India.7–10 These studies have offered evidence of the decrease of PM$_{2.5}$ and the increase of O$_3$ during the lockdown. The changes in PM$_{2.5}$ and O$_3$ are affected not only by emissions but also by meteorological conditions.11–14 A recent study suggested that PM$_{2.5}$ in China is sensitive to a few key meteorological parameters, such as wind speed, planetary boundary layer height (PBLH), temperature, and relative humidity (RH), while O$_3$ is mainly sensitive to temperature.15 Therefore, variations in meteorological conditions before and during the lockdown could contribute to the changes in PM$_{2.5}$ and O$_3$ concentrations. However, it remains unclear about the respective impacts of emission reduction and meteorological conditions on air quality during the lockdown.

This study aims to quantitatively examine the specific effects of both anthropogenic emission reduction due to COVID-19 lockdown and the variation of meteorological conditions on air quality in the Yangtze River Delta region (YRD), a more developed urban agglomeration in eastern China, which has been suffering both PM$_{2.5}$ and O$_3$ pollution in recent decades.16 Different scenarios were developed with specifically designed emissions and meteorological inputs, and then, the air quality in different scenarios was simulated to evaluate the...
Table 1. Emission Scaling Factors Based on Online Continuous Stack Emission Monitoring Data in Shanghai and Hangzhou Obtained by SAES

|            | Power | Iron and Steel | Petro Chemical | Chemical Industry | Industrial Stoves | Cement | Textile Industry | Other Industries | Transportation |
|------------|-------|----------------|----------------|-------------------|-------------------|--------|------------------|-----------------|----------------|
| NOx        | 0.60  | 1.04           | 0.73           | 0.80              | 0.49              | 0.28   | 0.97             | 0.05            | 0.10           |
| SO₂        | 0.87  | 0.98           | 0.74           | 0.45              | 0.38              | 0.38   | 1.42             | 0.06            | 0.10           |
| PM         | 0.76  | 0.91           | 0.96           | 0.50              | 0.39              | 0.37   | 0.74             | 0.02            | 0.10           |
| VOCs       | 0.74  | 0.98           | 0.81           | 0.58              | 0.42              | 0.34   | 1.04             | 0.04            | 0.10           |

*There is no emission monitoring on VOCs, CO, and NH₃, so the emission scaling factors for these species are the averages of those of NOx, SO₂, and PM.

Table 2. Configuration of Simulation Scenarios

| Case ID | NOx | VOCs | Others | Meteorology |
|---------|-----|------|--------|-------------|
| S0      | C   | C    | C      | 2020        |
| S1      | B   | B    | B      | 2020        |
| S2      | B   | C    | C      | 2020        |
| S3      | C   | B    | C      | 2020        |
| S4      | C   | C    | B      | 2020        |
| S5      | C   | C    | C      | 2019        |
| S6      | B   | B    | B      | 2019        |

*“B: business as usual. C: COVID-19.*

Four major cities, i.e., Shanghai, Nanjing, Hangzhou, and Hefei, were chosen for detailed analyses in this study. The observed concentrations of air pollutants were obtained from the publishing website of the China National Environmental Monitoring Center (http://106.37.208.233:20035/), including PM₂.₅, O₃, NO₂, SO₂, and CO. The PM₂.₅ composition and VOCs measurements were made at the SAES site, and the measurement methods have been described in previous studies and references therein.22–25

■ RESULTS AND DISCUSSION

Impacts of COVID-19 Lockdown on Air Quality in YRD. Figure 1a shows the predicted and observed daily PM₂.₅ and MDₐ₈ O₃ in S0 and S1 in the four major cities of YRD. Predictions of S0 and S1 are the same for the period before the lockdown. Predictions of PM₂.₅ and O₃ in S0 agree well with observations. The statistical results of the model performance of PM₂.₅ and O₃ are summarized in Table S1 in the Supporting Information. The results indicate that PM₂.₅ and O₃ in Nanjing, Hangzhou, and Hefei are both well predicted in S0 with most of the normalized mean bias (NMB) and normalized mean error (NME) meeting the model performance criteria proposed by Emery et al. (NMB within ±30% and NME ≤ 50% for PM₂.₅, NMB within ±15% and NME ≤ 25% for MDₐ₈ O₃).26 PM₂.₅ and O₃ in Shanghai are both underpredicted, which is likely due to the uncertainties in the emission inventory or in the scaling factors we used.

Figure 1b compares the observed and predicted relative changes of PM₂.₅, MDₐ₈ O₃, NO₂, SO₂, and CO in the four cities before and during the lockdown (S0). Significant decreases are observed in PM₂.₅ (~53% to ~31%), NO₂ (~76% to ~45%), and CO (~46% to ~14%). Changes in SO₂ are relatively small, about a 20% decrease in Shanghai, with no significant decrease in Nanjing and Hangzhou, and even a small increase (~5%) in Hefei (likely due to the unfavorable meteorological conditions offsetting the small decrease in SO₂ emissions). MDₐ₈ O₃ shows significant increases (31% to 88%). The model well captures the observed relative changes of PM₂.₅ and NO₂ in the four cities. MDₐ₈ O₃ changes are also well predicted except in Shanghai, where...
predicted change is substantially higher than observed change due to underprediction of MDA8 O₃ before the shutdown (especially on days of January 20−22). The predicted VOCs concentrations and changes also agree well with observed values, as shown in Figure S1. Therefore, the emission reduction adjustment used in our study is reasonable, which builds confidence in further analyses.

Figure 2a illustrates the average changes of PM₂.₅ and MDA8 O₃ in January and February 2020 due to emission reductions between S0 and S1 in the four cities (Figure S2 in the Supporting Information shows the spatial distributions of the changes). Emission reductions lead to significant PM₂.₅ decreases, with the least decrease of 23.02 µg/m³ (in Hangzhou) and the largest decrease of 34.24 µg/m³ (in Hefei) in February. In contrast, emission reductions cause MDA8 O₃ to increase by 13.52, 9.65, 9.54, and 6.97 ppb in Shanghai, Hangzhou, Nanjing, and Hefei, respectively, in February. The substantial reductions of emissions during the lockdown period result in 13 more days of good air quality (defined by AQI less than 100) in February in Nanjing and Hefei, while only 1 and 3 more good air quality days in Hangzhou and Shanghai, respectively.

The difference between S0 and S1 during January 23 to February 29 is considered as the effects of the emission reductions due to the COVID-19 lockdown since the meteorology is the same. The difference in pollutant concentration before and during the lockdown in S1 can be considered to be caused by meteorology variation since the...
emissions were not changed by COVID-19 (note that in S1, though there were no adjustments in emissions during January 23 to February 29, day-to-day variations in emissions still exist). As shown in Figure 2b, emission reductions contribute to PM$_{2.5}$ decrease by 37% to 55%, while the variation of meteorological conditions leads to 25% increase of PM$_{2.5}$ in Shanghai but contribute to PM$_{2.5}$ decrease only by 6%, 8%, and 14% in Nanjing, Hangzhou, and Hefei, respectively. Emission reductions contribute to MDA8 O$_3$ increase by 29% to 52%, and variation of meteorological conditions also contributes to MDA8 O$_3$ increase, with the range from 17% to 49%. Therefore, the emission reductions dominate the PM$_{2.5}$ decrease, and the effects of meteorological condition change on the PM$_{2.5}$ decrease are relatively small. However, both emission reductions and meteorological conditions contribute importantly to the O$_3$ increases during January 23 to February 29. The changes of meteorological conditions in Shanghai before and during the lockdown are shown in Figure S3, and their impacts on PM$_{2.5}$ and O$_3$ are discussed in the Supporting Information.

Impacts of Emission Reductions. Figure 3a shows the predicted daily PM$_{2.5}$ and MDA8 O$_3$ changes due to emission reduction in NOx (S0−S2), VOCs (S0−S3), others (S0−S4) and the overall impact of emissions reductions (S0−S1). On all days, the decrease of PM$_{2.5}$ concentration is mainly caused by the reduction of others, followed by NOx, while the impact of VOCs reduction is small. As stated earlier, others includes SO$_2$, CO, NH$_3$, and primary PM. NH$_3$ and SO$_2$ emissions were not significantly reduced by the lockdown, and CO has no effects on PM$_{2.5}$. Therefore, it is the emission reduction of primary PM that mainly drives the decrease of PM$_{2.5}$. Different from PM$_{2.5}$, the reduction of NOx emissions contributes to a significant increase in MDA8 O$_3$, which offsets the relatively small negative impact of VOCs reduction and causes the net increase of O$_3$. The reduction of other pollutants (i.e., SO$_2$, CO, NH$_3$, and primary PM) has almost no effects on MDA8 O$_3$.

Figure 3b displays the relative changes in PM$_{2.5}$ and MDA8 O$_3$ concentrations due to the reduction of NOx, VOCs, and others, and the overall impact of emission reduction. The overall emission reductions lead to a PM$_{2.5}$ decrease by 37% (in Nanjing) to 55% (in Shanghai). Others’ reduction causes a PM$_{2.5}$ decrease by 28% (in Nanjing) to 46% (in Shanghai). The reduction of NOx causes a 7% (in Hefei) to 10% (in Hangzhou) decrease, and VOCs emission reduction contributes to less than 1% in all the four cities. The reduction of NOx emissions has a tremendous positive impact on the MDA8 O$_3$ concentration in YRD, causing MDA8 O$_3$ to increase by 59%, 49%, 55%, and 38% in Shanghai, Nanjing, Hangzhou, and Hefei, respectively. On the contrary, VOCs emission reduction causes 8%, 7%, 9%, and 5% decreases in MDA8 O$_3$ in the four cities, respectively, and emission reduction of other pollutants has little effect on MDA8 O$_3$. The relationships of O$_3$ to VOCs and NOx during the winter episode are illustrated in Figure S4 and discussed in the Supporting Information.

O$_3$ increase could lead to unintentional change in the secondary PM$_{2.5}$ as O$_3$ is a major atmospheric oxidant and chemically involved in the formation of sulfate (SO$_4^{2-}$), nitrate (NO$_3^-$), and secondary organic aerosols (SOA). Figure 3c shows the changes of the major PM$_{2.5}$ components in S0. Most of the components decreased significantly during the lockdown, especially the primary components (such as elemental carbon (EC), primary organic aerosols (POA), and other primary components). A large amount of NOx emission reductions also lead to significant NO$_3^-$ and ammonium (NH$_4^+$) decreases, but the declining trend of NO$_3^-$ (−60% to −10%) is smaller than that of NO$_2$ (−76% to −45%). This is due to the increased atmospheric oxidizing capacity which promotes NO$_3^-$ formation and also due to increased NH$_3$ availability as SO$_4^{2-}$ concentrations decrease. More interestingly, SOA concentrations show increasing trends in YRD during the lockdown despite the emissions of VOCs being reduced, especially in Shanghai and Hangzhou. Further analysis shows that increased O$_3$ (and also increased hydroxyl radical, hydroperoxy radical, organic peroxy radicals) promotes SOA formations, which offset partially the decrease of PM$_{2.5}$ caused by the primary PM emission reductions. The enhanced secondary PM$_{2.5}$ formation is more distinct during the pollution events after the lockdown in Shanghai, which is illustrated in Figure S5. A recent observation-based study investigated the haze pollution events in Shanghai and revealed remarkable enhancement of formation efficiency of NO$_3^-$ during the COVID-19 lockdown, consistent to our modeling findings. This phenomenon was also observed in another study.

Significant but opposite changes have been observed in PM$_{2.5}$ (decrease) and O$_3$ (increase) in YRD during the
lockdown. Our analyses show that the PM$_{2.5}$ decrease is mainly caused by the emission reductions due to reduced anthropogenic activities, but the MDA$_8$ O$_3$ increase is driven by both emission reductions (+29% to +52%) and variation in meteorological conditions (+17% to +49%) in YRD. Emission reductions of others (mainly primary PM emissions) contribute to most of the PM$_{2.5}$ decrease, while NOx emission reduction dominates the MDA$_8$ O$_3$ increase. Even though the

Figure 3. (a) Averaged predicted daily PM$_{2.5}$ and MDA$_8$ O$_3$ in S0−S1, S0−S2, S0−S3, and S0−S4 from January 23 to February 29. (b) Relative changes of daily PM$_{2.5}$ and MDA$_8$ O$_3$ in S0−S1, S0−S2, S0−S3, and S0−S4 from January 23 to February 29. (c) Concentration changes in PM$_{2.5}$ major compositions in S0 before and after the lockdown.
meteorological conditions during the lockdown helped reduce PM$_{2.5}$ in most YRD regions, the meteorological conditions were generally worse compared to those in February 2019 (Figure S7). The quantitative contributions of the emissions and meteorological changes may change due to uncertainties in the emission estimates and uncertainties in the meteorological predictions, however, the general conclusions about the importance of the two factors should still hold.

Although O$_3$ has significantly increased during the lockdown period, it should be noted that O$_3$ concentration levels in YRD did not exceed the ambient air quality standards. In other words, the health risk of increased O$_3$ is relatively low. Therefore, health benefits can be expected from the largely decreased PM$_{2.5}$ concentration levels. Meanwhile, as indicated in our results and also found in another study, increased O$_3$ promotes secondary aerosol formation and offsets the decrease of PM$_{2.5}$ caused by the primary PM emission reductions, which partially reduce the health benefits of improved PM$_{2.5}$ during the lockdown. Currently, the YRD region faces both PM$_{2.5}$ and O$_3$ pollution and is seeking emissions control strategies to reduce the two pollutants simultaneously. Our results highlight that more carefully designed multipollutants (including NOx, VOCs, and primary PM) coordinated emissions control strategies are needed to achieve this goal in YRD.

**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.0c00511.

Table S1: Model performance of PM$_{2.5}$ and MDA8 O$_3$ in S0 and S1. Figure S1: Comparison of observed and predicted total VOCs concentrations and observed and predicted relative changes in different VOC species due to the COVID-19 lockdown in Shanghai. Figure S2: Spatial distributions of predicted PM$_{2.5}$ and MDA8 O$_3$ and changes between S0 and S1 during the lockdown period. Figure S3: Comparison of key meteorological parameters (temperature, RH, PBLH, and wind) before and after the lockdown in Shanghai. Figure S4: Responses of MDA8 O$_3$ in Shanghai to NOx and VOC reductions during the study period. Figure S5: Average concentration of PM$_{2.5}$ composition on polluted days and clean days before and after the lockdown. Figure S6: Spatial distributions of predicted PM$_{2.5}$ and MDA8 O$_3$ and changes between S0 and S5 during the lockdown period. Figure S7: Predicted PM$_{2.5}$ and MDA8 O$_3$ in S5 and S6 with 2019 meteorological conditions. (PDF)

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Notes
The authors declare no competing financial interest.

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