Environmental Science & Technology LETTERS

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

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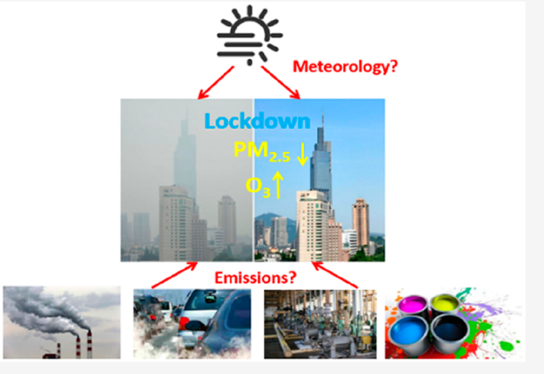
Cite This: https://dx.doi.org/10.1021/acs.estlett.0c00511 Read Online

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

Received: June 24, 2020
Revised: September 12, 2020
Accepted: September 14, 2020
Published: September 14, 2020

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
SO_2	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[a]	0.74	0.98	0.81	0.58	0.42	0.34	1.04	0.04	0.10

[a]There is no emission monitoring on VOCs, CO, and NH_3, so the emission scaling factors for these species are the averages of those of NOx, SO_2, and PM.

effects of emission reductions and meteorological variation on average daily $PM_{2.5}$ and daily maximum 8 h average (MDA8) O_3 concentrations.

MATERIALS AND METHODS

Air quality in the YRD region was simulated using the Community Multiscale Air Quality (CMAQ) model, version 5.2,[17,18] with the photochemical mechanism of SAPRC-07.[19] The meteorology fields were simulated using the Weather Research Forecasting (WRF) model, version 4.0. Horizontal grid resolution is 4 km × 4 km. Model configurations of WRF and CMAQ followed the study by Hu et al.[20] The modeling period is from December 29, 2019, to February 29, 2020. The first three days were spin-up, and therefore, only January 1 to February 29 were included in the analyses, whereas January 1 to 22 is before the COVID-19 lockdown, January 23 to February 29 is during the lockdown. The baseline anthropogenic air pollutant emissions of 2017 in YRD were estimated by the Shanghai Academy of Environmental Sciences (SAES).[21] The emission reductions of NOx, SO_2, and PM during the lockdown period were estimated using the online continuous stack emission monitoring data in Shanghai and Hangzhou obtained from the National Pollution Source Monitoring Information Management and Sharing Platform (https://123.127.175.61/). The emission scaling factors for NOx, SO_2, and PM were calculated by comparing the emissions and traffic amounts during the lockdown to those before the lockdown. There was no emission monitoring on VOCs, CO, and NH_3; therefore, the emission scaling factors for NOx, SO_2, and PM were averaged for each source and used as the scaling factors for these species. Reduction in the transportation sector was estimated based on the real time traffic flow data obtained by SAES. The emission adjustment ratios are listed in Table 1, and for all other anthropogenic sources not included in the table, no changes were adjusted. Other emissions (i.e., biogenic emissions, open burning, windblown and sea salt emissions) followed the study by Hu et al.[20]

To investigate the effects of emission reduction and meteorological conditions on air quality, seven scenarios were developed (Table 2). The base case scenario S0 used the adjusted emissions for the period during the lockdown. The business as usual scenario S1 used the original anthropogenic emission inventory of YRD for the entire simulation period. 2020 Meteorology was used in S0−S4, while 2019 meteorology (simulated by the WRF model with the same model configurations as the 2020 episode) was used in S5 and S6. Compared to S0, the S2−S4 scenarios used the same emissions except for NOx, VOCs, and other pollutants (pollutants other than NOx and VOCs, including SO_2, CO, NH_3, primary PM). The emissions of S5 and S6 were the same as S0 and S1, respectively.

Table 2. Configuration of Simulation Scenarios[a]

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

[a]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 $PM_{2.5}$, O_3, NO_2, SO_2, and CO. The $PM_{2.5}$ 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 $PM_{2.5}$ and MDA8 O_3 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 $PM_{2.5}$ and O_3 in S0 agree well with observations. The statistical results of the model performance of $PM_{2.5}$ and O_3 are summarized in Table S1 in the Supporting Information. The results indicate that $PM_{2.5}$ and O_3 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 $PM_{2.5}$, NMB within ±15% and NME ≤ 25% for MDA8 O_3).[26] $PM_{2.5}$ and O_3 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 $PM_{2.5}$, MDA8 O_3, NO_2, SO_2, and CO in the four cities before and during the lockdown (S0). Significant decreases are observed in $PM_{2.5}$ (−53% to −31%), NO_2 (−76% to −45%), and CO (−46% to −14%). Changes in SO_2 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 SO_2 emissions). MDA8 O_3 shows significant increases (31% to 88%). The model well captures the observed relative changes of $PM_{2.5}$ and NO_2 in the four cities. MDA8 O_3 changes are also well predicted except in Shanghai, where

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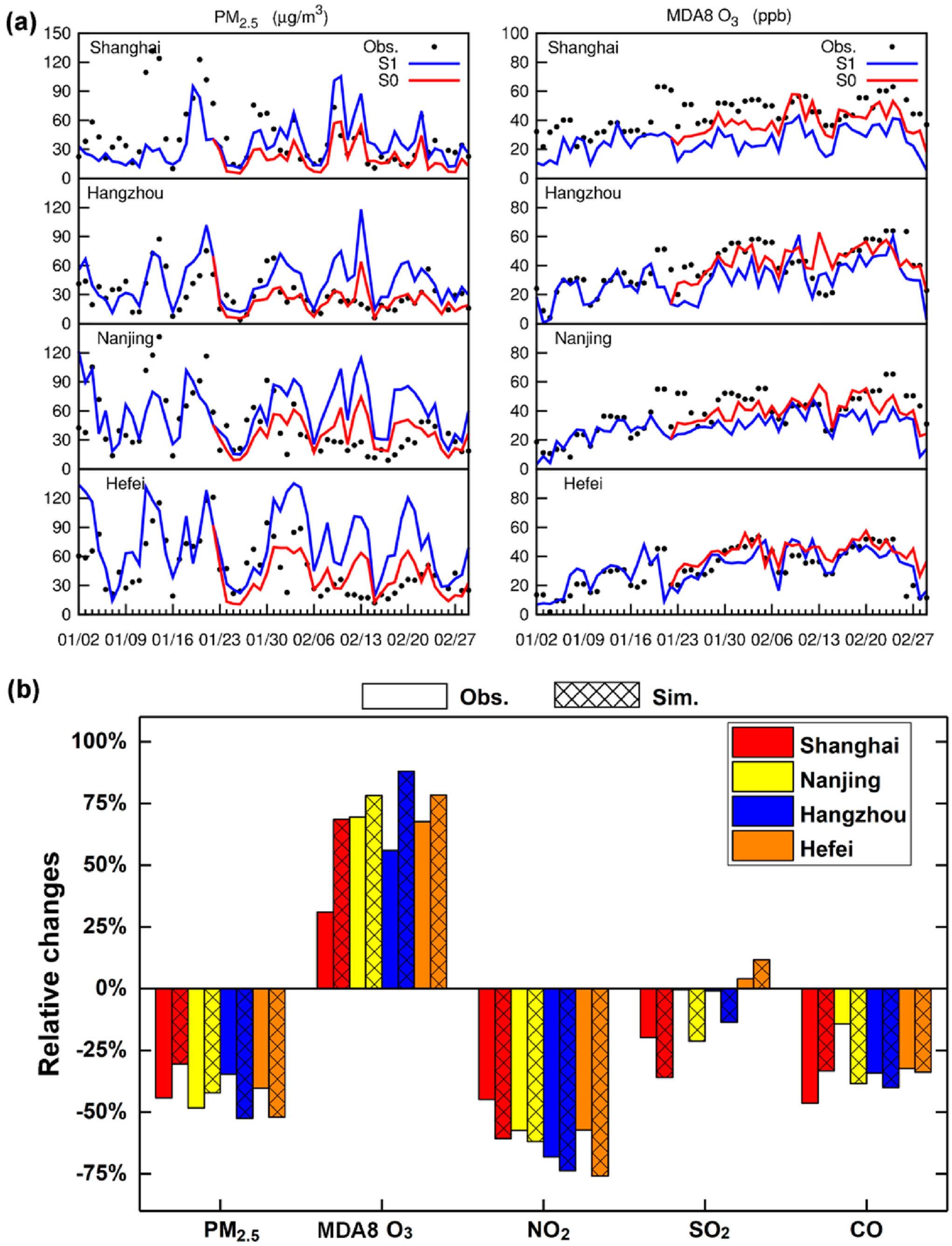

Figure 1. (a) Predicted daily $PM_{2.5}$ and MDA8 O_3 in S0 and S1 compared to observations. (b) Relative changes in observed and simulated air pollutants concentration in January 23 to February 29, 2020, compared to January 1− 22.

predicted change is substantially higher than observed change due to underprediction of MDA8 O_3 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 $PM_{2.5}$ and MDA8 O_3 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 $PM_{2.5}$ decreases, with the least decrease of 23.02 $\mu g/m^3$ (in Hangzhou) and the largest decrease of 34.24 $\mu g/m^3$ (in Hefei) in February. In contrast, emission reductions cause MDA8 O_3 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

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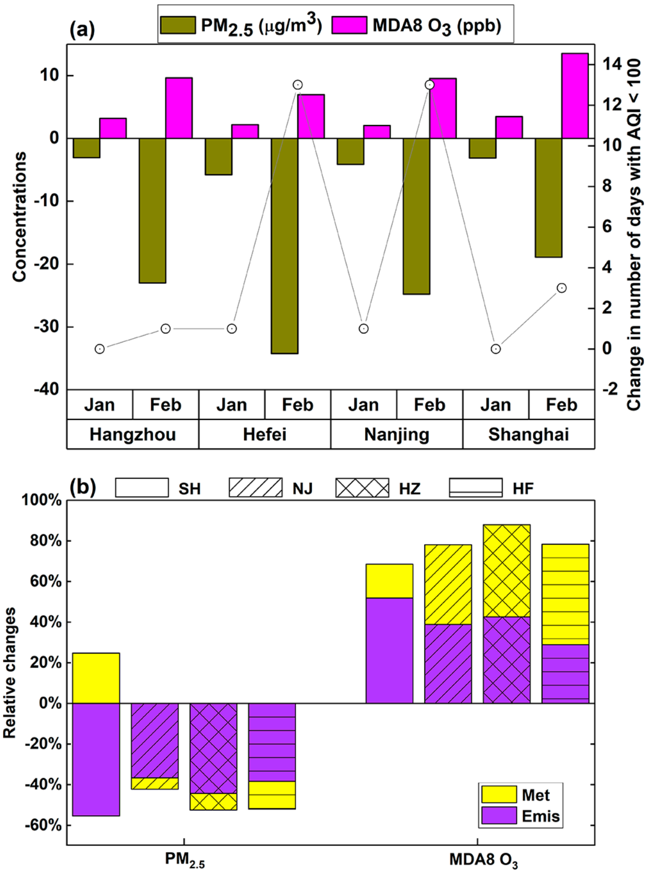

Figure 2. (a) Average changes (S0−S1) of PM2.5 and MDA8 O3 and days of good air quality (AQI < 100) due to COVID 19 in January and February. (b) Impacts of meteorology vs emission on the changes of PM2.5 and MDA8 O3 from January 23 to February 29 compared to January 1 to January 22 in the four YRD cities, respectively. The graphic textures represent the cities, and the yellow color represents the impacts of meteorology, while the purple color represents the impacts of emission reductions.

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,[27] consistent to our modeling findings. This phenomenon was also observed in another study.[9]

Significant but opposite changes have been observed in $PM_{2.5}$ (decrease) and O_3 (increase) in YRD during the

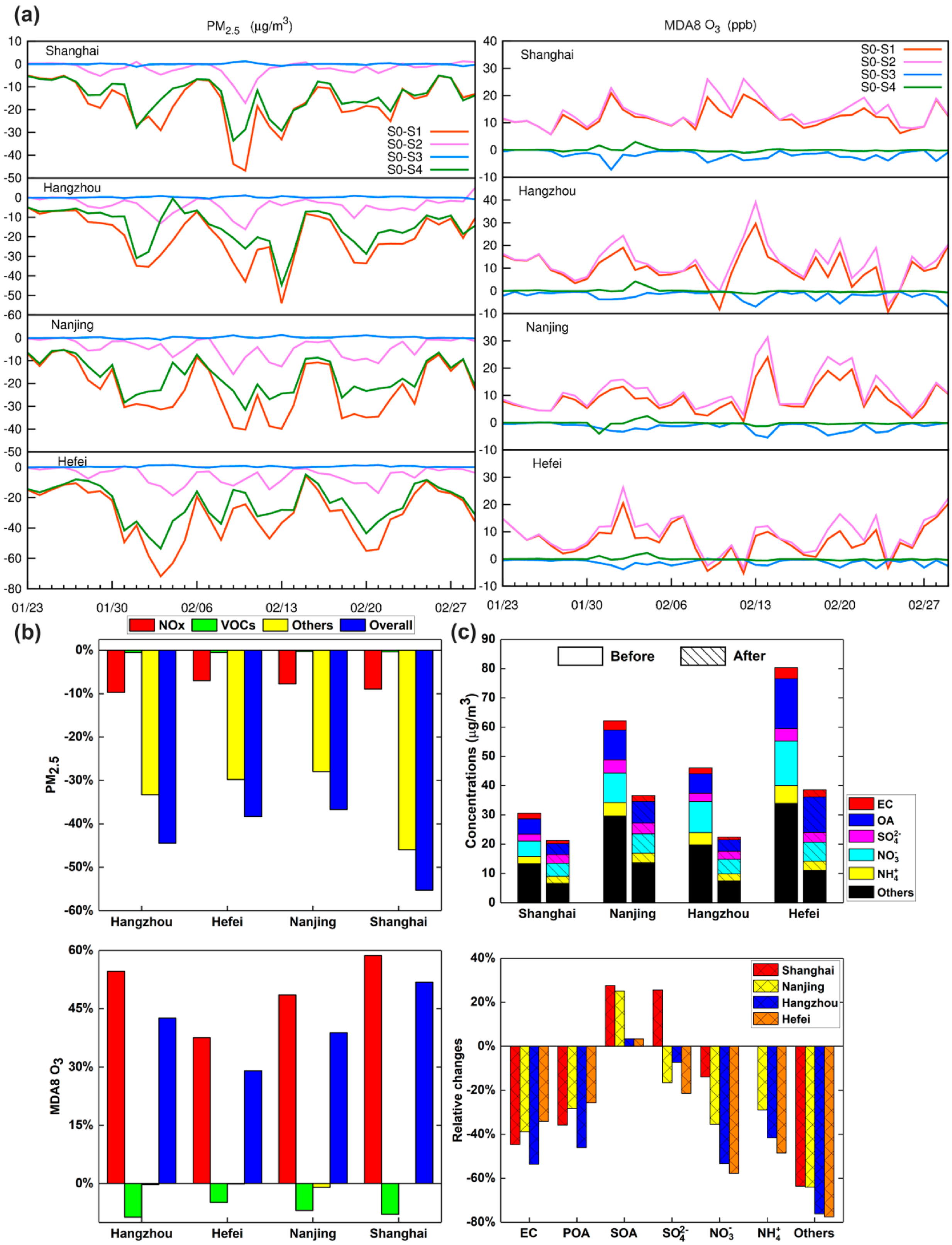

Figure 3. (a) Averaged predicted daily $PM_{2.5}$ and MDA8 O_3 in S0−S1, S0−S2, S0−S3, and S0−S4 from January 23 to February 29. (b) Relative changes of daily $PM_{2.5}$ and MDA8 O_3 in S0−S1, S0−S2, S0−S3, and S0−S4 from January 23 to February 29. (c) Concentration changes in $PM_{2.5}$ major compositions in S0 before and after the lockdown.

lockdown. Our analyses show that the $PM_{2.5}$ decrease is mainly caused by the emission reductions due to reduced anthropogenic activities, but the MDA8 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 MDA8 O_3 increase. Even though the

https://dx.doi.org/10.1021/acs.estlett.0c00511
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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,[9] 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 PM2.5 and MDA8 O3 in S5 and S6 with 2019 meteorological conditions. (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the National Key R&D Program of China (2018YFC0213800), the National Natural Science Foundation of China (41975162, 41675125, 21777101, and 41705102), and Jiangsu Environmental Protection Research Project (2016015).

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