COMPREHENSIVE INSIGHTS INTO O3 CHANGES DURING THE COVID-19 FROM O3 FORMATION REGIME AND ATMOSPHERIC OXIDATION CAPACITY

Shengqiang Zhu1, James Poetzscher1,2, Juanyong Shen3, Siyu Wang1, Peng Wang4, and Hongliang Zhang1,2

1Department of Environmental Science and Engineering, Fudan University, Shanghai, China, 2School of Environmental Science and Engineering, Hong Kong Polytechnic University, Hong Kong, China, 3School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China, 4Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hong Kong, China, 5Institute of Eco-Chongming (IEC), Shanghai, China

Abstract Economic activities and the associated emissions have significantly declined during the 2019 novel coronavirus (COVID-19) pandemic, which has created a natural experiment to assess the impact of the emitted precursor control policy on ozone (O3) pollution. In this study, we utilized comprehensive satellite, ground-level observations, and source-oriented chemical transport modeling to investigate the O3 variations during the COVID-19 pandemic in China. Here, we found that the significant elevated O3 in the North China Plain (40%) and Yangtze River Delta (35%) were mainly attributed to the enhanced atmospheric oxidation capacity (AOC) in these regions, associated with the meteorology and emission reduction during lockdown. Besides, O3 formation regimes shifted from VOC-limited regimes to NOx-limited and transition regimes with the decline of NOx during lockdown. We suggest that future O3 control policies should comprehensively consider the effects of AOC on the O3 elevation and coordinated regulations of the O3 precursor emissions.

Plain Language Summary Severe ozone (O3) pollution has been a public concern in China during the last decade. Due to the 2019 novel coronavirus (COVID-19) pandemic, China has implemented the strict restrictions, leading to the significant decline of economic activities and the associated emissions. However, the O3 levels have been elevated in vast areas of China during the COVID-19 lockdown period. In this study, we applied the comprehensive satellite, ground-level observations, and source-oriented chemical transport modeling to investigate the O3 elevation during the COVID-19 lockdown periods. Importantly, our results showed that O3 has increased significantly in North China Plain (40%) and Yangtze River Delta (35%) during lockdown, which attributed to the enhanced atmospheric oxidation capacity (AOC) associated with the meteorology and emission reduction. Besides, we found the O3 formation regimes shifted from VOC-limited to NOx-limited due to the lower NOx during lockdown. In the future, we suggest that O3 control policies ought to ensure a balance between emitted NOx and VOCs to maintain stable O3 formation regimes and AOC levels and thereby control O3 emissions.

1. Introduction

Beginning in January 2020, a novel coronavirus (COVID-19) began rapidly spreading throughout China, first in Wuhan, and then in other major cities (Hsiang et al., 2020; Tisdell, 2020). In response, to prevent the spread of COVID-19, the first lockdown was implemented on January 23, suspending nonessential traffic in Wuhan, the epicenter of the outbreak. Over the following days, major cities throughout China issued similar travel restrictions and stringent lockdown measures, affecting over half a billion residents. These restrictive measures resulted in substantial reductions in human activities, which consequently induced unprecedented decreases in anthropogenic emissions of air pollutants, especially from the industry and transportation sectors (Dai et al., 2020; Venter et al., 2020). In particular, during the lockdown, NOx levels in Eastern China were estimated to have decreased by ~65% compared to the same period in 2019, mainly due to the reduction of vehicle emissions (Griffith et al., 2020; Huang et al., 2020). Similarly, other pollutants...
such as SO2 and CO also decreased. In contrast, during the same period, ozone (O3) increased significantly with a nationwide increase of 47.3% (Huang et al., 2020; Le et al., 2020; Y. B. Zhao et al., 2020).

Besides the lockdown period, China experienced persistent O3 pollutions in recent five years, especially in urban areas (Fang et al., 2019; K. Li, Jacob, et al., 2019; X. Lu et al., 2018). O3 is formed through nonlinear photochemical reactions of nitrogen oxides (NOx = NO + NO2) and volatile organic compounds (VOCs; Liu et al., 2012). The O3 sensitivity regime, determined by the relative abundance of VOCs and NOx, plays a significant role in O3 formation (L. Jin et al., 2008; K. D. Lu et al., 2010). Previous studies have reported that the elevated O3 during lockdowns was mainly attributed to the enhanced atmospheric oxidation capacity (AOC; Goldstein & Galbally, 2007; Le et al., 2020), reflected by the levels of major oxidants such as hydroxyl radical (OH) and nitrate radical (NO3; Mochida et al., 2003). AOC was controlled both by emission and meteorological fields through nonlinear photochemistry (T. Feng et al., 2020). Specifically, NO2 is defined as the main sink of OH radical, as it reacts with OH to form nitric acid (HNO3; Chang et al., 2018; Sadanaga et al., 2005). During the lockdown, the drastic decreases in NO2 levels increased OH concentration, which then reacted with VOCs, facilitating the formation of secondary pollutants (Yang et al., 2020). Unfortunately, the current understanding of AOC and secondary pollution is still limited, and the previous research methods are relatively simple, either ground-level observation or modeling methods (Feng et al., 2019; Sheehy et al., 2010; Shiu et al., 2007). The COVID-19 lockdown provides an important opportunity to study the interaction between O3 levels, O3 formation regime and AOC attributed to emission and meteorology. In addition, the combination of ground-level observations, satellite retrievals and modeling methods offers a comprehensive analysis on O3 formation.

In this study, we used ground-level and satellite data to identify changes in O3 levels and its associated precursors (NO2 and HCHO) during the COVID-19 lockdowns in China. The Community Multiscale Air Quality (CMAQ) model was also applied to analyze the characteristics of air quality in the same period. The roles of the O3 sensitivity regime and AOC were also discussed to provide an in-depth explanation for the increase in O3. We found that O3 elevations during the COVID-19 lockdown period in the NCP and YRD were mainly controlled by enhanced AOC, which was attributed to the reductions of anthropogenic emissions and meteorological variations. In contrast, O3 decreased slightly in the Pearl River Delta (PRD). The results aim to formulate more effective emission control policies, particularly focused on reducing AOC to battle the persistent O3 pollution in China.

2. Material and Methods

2.1. Satellite Data

TROPOMI products are available for free through the Copernicus Open Access Hub (https://scihub.copernicus.eu, last access: September 2020). In this study, we utilized two TROPOMI datasets, tropospheric NO2 column number density, and tropospheric HCHO column number density, and re-projected them into the same domain as model simulations by using a Lambert projection. As suggested by the data provider, we have filtered the source data to remove pixels with quality assurance (QA) values less than 75% for tropospheric NO2 column number density datasets and 50% for tropospheric HCHO column number density.

2.2. The Emission Reductions Due to the COVID-19 Lockdown

The emission reductions based on the bottom-up inventory model of Multi-resolution Emission Inventory for China (MEIC) have been estimated and validated in previous studies (Huang et al., 2020). The MEIC model consists of five emission sectors: industry, power, residential, transportation, and agriculture. The thermal power generation has decreased 8.9% in the January and February of 2020 than in 2019 while China has generated 1.7% more thermal power in January and February 2019 than in 2018. Such a difference in the growth rates between 2019 and 2020 was assumed to the impact of COVID-19 restrictions. The same technique has been implemented in the industrial sector. For the residential sector, the commercial activity level of boilers and stoves has been evaluated in the emission adjustment process. Meanwhile, national traffic volume data including on-road and off-road conditions have been adopted for transportation emission adjustment. The detailed information can be found in Table S1 and the emission reduction data proved to be reliable (Huang et al., 2020).
2.3. Future Emission Scenarios

Three future emission scenarios including NOx reduction, VOC reduction, and NOx and VOC reduction scenarios have been designed in this study. In NOx reduction scenario, we further reduced the NOx emissions by 50% from the levels of the Lockdown scenario. In VOC reductions scenario, we further reduced the VOC emissions by 50% from the levels of the Lockdown scenario. And in NOx and VOC reduction scenarios, we further reduced both the NOx and VOC emissions by 50% from the levels of the Lockdown scenario.

2.4. The CMAQ Model Configuration

A modified CMAQ model v5.0.2 with an expanded SAPRC-99 photochemical mechanism was applied to simulate the O3 levels and track the sources of its precursors in China (Wang et al., 2019, 2020; Ying & Krishnan, 2010; H. Zhang & Ying, 2011). The time interval for which the simulation was conducted spanned from January 1 to March 31, comprising the Pre-lockdown (January 6 to 22), Lockdown (January 23 to February 29), and Post-lockdown (March 1 to 31) periods. Simulations for the same period in 2019, a control period during which there were no emission reductions due to the COVID-19 induced lockdowns, were also conducted. The model domain included China and its surrounding countries (Figure S1), with a horizontal resolution of 36 × 36 km (127 × 197 grids). The vertical extent was ∼20 km from the surface and divided into 18 sigma layers with the first layer height at a height of ∼35 m from the surface. The detailed model validation can be found in the supporting information.

Specifically, NO2 and HCHO concentrations ($\sum_{j} a \times H_i \times \text{con}_j$) from 17 vertical layers (with the highest layer height of ∼10 km) in the CMAQ model were added up to ascertain their tropospheric column concentrations ($\sum_{j} a \times \text{TCR}_{\text{NO}_2}$) as shown in Equation 1:

$$\text{TCR}_j = \sum_{i=1}^{17} a \times H_i \times \text{con}_j$$

Here, $H_i$ was each layer height acquired by meteorological simulation and $a$ was the conversion factor of CMAQ modeling concentration and column concentration. In our study, the O3 formation regimes were categorized into VOC-limited, NOx-limited and transition regimes based on the formaldehyde nitrogen concentrations ratio ($R_1$) as shown in Equation 2 (X. M. Jin & Holloway, 2015; Tang et al., 2012).

$$R_1 = \frac{\text{TCR}_{\text{HCHO}}}{\text{TCR}_{\text{NO}_2}}$$

Here, we set a $R_1 < 1.0$ as a VOC-limited regime, a $R_1 > 2.0$ as a NOx-limited regime and a $R_1$ between 1.0 and 2.0 as a transition regime (Duncan et al., 2010; Witte et al., 2011). Also, we adopted two other O3 formation regime indices $R_2$ and $R_3$ for comparison with $R_1$. The detailed information about $R_2$ and $R_3$ could be found in the supporting information.

3. Results and Discussion

3.1. Significant O3 Variations During the Lockdown

According to surface observation, changes in China’s surface maximum daily 8 h (MDA8) O3 show significant spatial variations from Pre-lockdown to Post-lockdown. During the Lockdown, O3 levels increase in large areas throughout northern and central China compared to the Pre-lockdown, while they decreased in South China (Figure 1a), consistent with previous studies (Huang et al., 2020; Le et al., 2020; Y. B. Zhao et al., 2020). The most prominent O3 increase occurred in the NCP (Figure 1b), with a mean MDA8 O3 increase of 54% (from 24 to 37 ppb; Figure 1c). In Baoding and Shijiazhuang (major cities in the NCP), O3 increased by over 100%. Moreover, in the YRD, a noticeable MDA8 O3 increase of 44% (from 26 to 38 ppb) was observed. During Post-lockdown, observed O3 concentrations continued to increase in the NCP and YRD, partially due to the rising temperature (Figure S2). O3 variation is more complex in the PRD, however. In general, O3 levels decrease from Pre-lockdown to Post-lockdown. But in Guangzhou, the most populated city of PRD, an increase in O3 was observed. Considering the similar temperature levels between
In addition, the changes of O₃ levels between the same periods of Pre-lockdown and Lockdown in 2019 were not as obvious as in 2020 (Figure S3a). Compared to the same period of Lockdown in 2019, heightened O₃ pollution was observed in the NCP and YRD during the Lockdown in 2020 (Figure S3b). Although O₃ precursors decreased drastically in these regions, mean MDA8 O₃ levels were 14%–19% higher than in 2019. In contrast, in the PRD, the mean MDA8 O₃ during the Lockdown of 2019 is close to (or even slightly higher) that in 2020, and the opposite of the trend observed in the other regions. O₃ levels were controlled by AOC, which was mainly attributed to emission and meteorological fields (T. Feng et al., 2020; K. H. Zhao et al., 2021). The detailed meteorological conditions during three periods (Pre-lockdown, Lockdown, and Post-lockdown) in 2020 were presented in Figure S2 and Tables S6a and S6b. Furthermore, the sensitivity experiments were conducted to investigate the impacts of meteorology and emission reduction on O₃ elevation (Figure S12). The results showed that both meteorology and emission reduction played important roles in O₃ elevation in NCP. The meteorology contributed more to daytime O₃ elevation and the emission reduction contributed more to the nighttime O₃ elevation in YRD due to the weaker NO-titration effects (Huang et al., 2020). Meanwhile, it is more critical to deeply understand the associations of O₃ formation regime, AOC and O₃ levels with the impacts of meteorology and emission reduction, which provided valuable O₃ control policies.

Pre-lockdown and Lockdown over China, these variations are more related to the sudden reductions of O₃ precursors.

Figure 1. (a) Observed and CMAQ predicted surface MDA8 O₃ in China during Pre-lockdown and Lockdown periods. The dots represent the observed MDA8 O₃ values; SJZ, Shijiazhuang; BD, Baoding; GZ, Guangzhou; (b) Observed and CMAQ predicted MDA8 O₃ growth rate during Pre-lockdown and Lockdown periods (The growth rate was calculated by dividing MDA8 O₃ differences between 2020 and 2019 years by the absolute MDA8 O₃ values in 2019 as shown in Equation 8 in the supporting information); (c) Observed mean MDA8 O₃ in the NCP, YRD, and PRD regions. CMAQ, Community Multiscale Air Quality; MDA, maximum daily.
3.2. Changes of O₃ Precursors and Formation Regimes

Given that the ratio of HCHO to NO₂ determines the O₃ formation regimes, HCHO and NO₂ are considered the most important precursors of O₃ (X M Jin et al., 2017). The satellite column data and CMAQ model have revealed significant reductions of NO₂ throughout much of China, especially in NCP and YRD regions (Figure S4a). According to the satellite data, NO₂ in the NCP, YRD, and PRD regions declined by 59.61%, 63.28%, and 44.03% during the Lockdown respectively. These reductions are mainly attributed to the significant decline of NOₓ emissions from industry, power, and transportation sectors illustrated by the source apportionment analysis (Table S7).

However, no noticeable changes were observed in the HCHO concentration during the Lockdown. The spatial distribution of HCHO, similar to that of NO₂, exhibits higher levels in southeast China, whereas in western China, due to the low anthropogenic VOCs emissions, the HCHO concentration is relatively low (Bo et al., 2008; M. Li, Zhang, et al., 2019). The HCHO in the atmosphere is mainly formed through direct emissions from industrial and biogenic sectors and through secondary sources such as the oxidation reaction between VOCs and OH. During the Lockdown, emissions of HCHO and other VOCs declined significantly (~37%) in China (Table S1) and therefore might have reduced HCHO levels. However, the enhanced AOC (Huang et al., 2020) during Lockdown likely promoted the formation of HCHO from secondary sources, offsetting the impact of the decline in HCHO emissions and explaining why HCHO levels remained relatively constant. Also, the background HCHO was relatively constant and contributed most to the total HCHO concentrations as shown in our source apportionment analysis (Table S7). The constant background HCHO levels can be mainly explained by the oxidation of methane, which has a long lifetime and relatively stable concentrations (Boeke et al., 2011; X. M. Jin & Holloway, 2015).

In general, the O₃ sensitivity regimes in China shifted from VOC-limited to NOₓ-limited and transition categories during the Lockdown, as indicated by both satellite data and model simulations (Figure 2b and Table S8). The comparative experiments which used two other O₃ formation regime indices R₁ and R₃ also show the similar results (Figures S16a and S16b). During the Pre-lockdown period in 2020, the VOC-limited regime dominates in the NCP, YRD, and PRD regions due to the relative abundant NOₓ emissions from industry and transportation sectors, consistent with the previous studies (Xing et al., 2011). However, during the Lockdown period, VOC-limited regimes shifted to NOₓ-limited and transition regimes in these regions. The percentage of NOₓ-limited regimes in the NCP, YRD, and PRD regions during the Lockdown period increased from 11%, 37%, and 31% to 56%, 65%, and 69%, respectively based on R₁. These changes in the O₃ formation regime and NO₂ and HCHO concentrations in 2019 were not as obvious as in 2020 (Figure S5a); NO₂ and HCHO concentrations during the periods in 2019 that correspond to the Pre-lockdown and Lockdown periods in 2020 remained relatively constant compared with 2020, explaining the lack of the same remarkable variations in the O₃ formation regimes as in 2020 (Figure S5b). We have slightly overestimated the NO₂ and HCHO concentrations in keys regions (Figure 2a), which may lead to uncertainties in the determination of the O₃ formation regime. In particular, the modeling results show the larger areas of VOC-limited and transition regimes compared to the satellite retrieval data (Figure 2b). The differences in the simulated and satellite retrieved O₃ formation regime in 2019 are due to the uncertainties from both satellite data and CMAQ model (Figure S5b). Such NO₂ uncertainty originates from satellite errors in slant column retrieval, cloud and aerosol correction algorithm, surface albedo, and a priori NO₂ profile shape (Dimitropoulou et al., 2020; Ialongo et al., 2020). Besides, the uncertainty of chemical transport models is mainly due to emission inventories, associated with activity levels, emission source fraction, and emission factors (Cheng et al., 2020; Hu et al., 2017). In general, our model performance was validated against ground-level observations (Tables S3 and S5) and similar O₃ formation regime distributions have been reported in previous studies (X. M. Jin & Holloway, 2015). Also, the spatial ranges of O₃ formation regimes based on R₁, R₂, and R₃ differ from each other in Figures S16a and S16b, which were mainly due to the uncertainties in the quantitative relationships of O₃ and its precursors (Liang et al., 2006). In particular, O₃ formation regime indices are subject to many uncertainties, including deposition rates, aerosol interactions and case-to-case variations (Jimenez & Baldasano, 2004). The uncertainty is relatively higher for indices R₃ since H₂O₂ is vulnerable to reaction rate and mechanism uncertainties as shown in Figure S16 (Sillman, 1995). Generally, the conversion trends of the O₃ formation regime shift based on R₁, R₂, and R₃ were consistent in these
scenarios (Figure S16), and the results of the $O_3$ formation regime distributions based on $R1$, $R2$, and $R3$ were relatively reliable compared to the previous studies (Jimenez & Baldasano, 2004).

Consequently, $O_3$ levels increased in the NCP and YRD regions during the Lockdown period in 2020, with the pronounced reductions of $NO_x$ (X. M. Jin & Holloway, 2015). Meanwhile, we were more concerned about the impacts of AOC on $O_3$ levels, which were associated closely with the shift of $O_3$ formation regime.

### 3.3. The Dominating Role of the Enhanced AOC in $O_3$ Formation

Our model simulations demonstrated significantly enhanced AOC in the NCP and YRD regions (Figure 3b and 3d), which is consistent with the variation of $O_3$ concentrations. $HO_x$ (OH and HO$_2$) radicals, the main daytime oxidant, increased significantly in central and northern China with the highest growth rates of 0.06 and 2.71 ppt for OH and HO$_2$ radical, respectively due to the relatively low levels of NO$_x$, the primary HO$_x$ sink (Figures 3a and S6a). Specifically, in the NCP, YRD, and PRD regions, the average increase in HO$_x$ was 0.79, 0.92, and 0.17 ppt, respectively. In both Baoding and Shijiazhuang, OH radicals have increased over 98% during the Lockdown (up to 0.019 and 0.021ppt, respectively). HO$_2$ radicals have increased over 580% (up to 0.92 and 0.95ppt, respectively) in these two cities. The rise in OH and HO$_2$ radicals could be the
leading cause of the O3 increase during the Lockdown period in the NCP and YRD regions given their strong association with O3 production (Kentarchos & Roelofs, 2003; Ren et al., 2013; Q. Zhang et al., 2014). The OH radicals oxidize VOCs to produce peroxy radicals such as HO2, which covert NO to NO2 without consuming O3. Then the NO2 produces O3 through photolysis reactions, leading the O3 accumulation as shown in the mechanism scheme (Figure S7; Pollack et al., 2013; Tan et al., 2019).

At the same time, the NO3 radical, the primary nighttime oxidant, has increased significantly in the NCP and YRD regions during the Lockdown (averaged 0.49 and 0.29 ppt, respectively). In addition, NO3 radicals have increased by 853% (up to 0.7 ppt) and 612% (up to 0.84 ppt) in Baoding and Shijiazhuang cities respectively during Lockdown. This phenomenon can be explained by the low levels of VOC and NO2, both of which serve as important sinks for the NO3 radical (Lucas & Prinn, 2005; Figure S6a). In contrast, in the PRD region, levels of the NO3 radical declined (up to −0.21 ppt; Figure 3c). Diurnal variations of OH, HO2, and NO3 radicals also showed AOC was enhanced obviously in NCP and YRD regions (Figures S8–S10). The less enhancement of AOC are found in 2019 compared to 2020 during the same periods (Pre-lockdown and Lockdown), especially in the YRD (Figure S11) and thus leading to fewer O3 elevation. The sensitivity experiment results also indicated the important role of AOC associated with emission reductions and meteorology in O3 elevation in 2020 (Figures S12–S15). Given the enhanced AOC, a significant increase in O3 was observed in the NCP and YRD regions. In the PRD, however, the constant AOC was responsible for a slight decrease in O3. Importantly, in the NCP and YRD regions, the increase in O3 enhanced the AOC due to local photochemistry (Asaf et al., 2009; Geyer et al., 2001), creating a vicious cycle of heightening O3 levels.

Significantly, our results of future emission scenarios showed the consistency between O3 formation regime and AOC levels. Specifically, O3 formation regimes were further shifted to NOx-limited and transition regimes in NCP and YRD regions in NOx reduction scenario compared to Lockdown (Figure S16c). Simultaneously, AOC levels were enhanced obviously in NCP and YRD regions, which caused the further
O3 elevation in these regions (Figure S17). Our diurnal results also showed the elevation of O3 and AOC in these two regions, especially in NCP (Figure S18). The further elevation of O3 and AOC could be explained by that there were still around half of areas categorized as VOC-limited and transition regimes in NCP and YRD regions during Lockdown (Table S8), even though the O3 formation regimes in many areas were shifted from VOC-limited to NOx-limited and transition regimes during that period. On the contrary, the levels of O3 and AOC both decreased in VOC reduction scenario (Figure S17). O3 formation regimes were also shifted from NOx-limited and transition regimes to VOC-limited regimes. Meanwhile, a slight elevation of AOC and O3 has been found in NCP regions in NOx and VOC reduction scenario, accompanied by a slight O3 formation regime shift from VOC-limited regimes to NOx-limited and transition regimes.

In the future, we underscore the importance of a carefully tailed and balanced strategy of O3 precursor emission to maintain steady AOC levels, which in turn control the O3 concentrations. Specifically, we ought to adopt the synergistic control of NOx and VOC emissions in central and southern China as shown in Figure S17. Meanwhile, we should still pay more attention to the reduction of VOC emissions in NCP and YRD regions, in order to maintain the relatively low levels of AOC and O3. Arbitrary further reduction of NOx emissions beyond lockdown levels would not control the O3 levels in NCP and YRD regions due to that there were still many areas belonging to VOC-limited and transition regimes.

4. Conclusion and Implication

Based on this analysis, we have devised a conceptual scheme to demonstrate the roles of the O3 formation regime shift and enhanced AOC on O3 level during the COVID-19 Lockdown period in China (Figure 4). O3 formation regime has shifted from VOC-limited to NOx-limited with the impact of dramatic emission reduction during Lockdown. Besides, AOC was enhanced significantly with the decline of NOx, which contributed to the O3 elevation during Lockdown. Also, the importance of balanced emission control policies has been emphasized for reducing the O3 pollution events in China according to the modeling of the future emission scenarios. Previous policies, which have focused on the arbitrary reduction of primary emission of NOx, SO2, and VOCs, need to be reconsidered as different regions have different O3 sensitivity, and current policies might unintentionally enhance AOC in certain regions, thereby heightening ozone levels. With the effects of AOC enhancement accompanied by the O3 formation regime shift, O3 might be elevated in turn. In the future, we recommend that O3 control policies of emission reduction utilize knowledge regarding the associations of O3 formation regime, AOC variations, and O3 levels. Specifically, we believe emission control policies ought to ensure a balance between emitted NOx and VOCs to maintain stable O3 formation regimes and thereby control O3 emissions.
Conflict of Interest
The authors declare no conflicts of interest relevant to this study.

Data Availability Statement
TROPOMI production data could be found online at (https://scihub.copernicus.eu, last access: January 2021). Ground-level observation data were publicly available at (https://doi.org/10.6084/m9.figshare.13524683.v1, last access: January 2021; https://doi.org/10.6084/m9.figshare.13524686.v1, last access: January 2021). Surface meteorological data could be found from National Climate Data Center (https://www.ncdc.noaa.gov/data-access, last access: January 2021). The Multi-resolution Emission Inventory for China could be found at (http://www.meicmodel.org, last access: January 2021).

Acknowledgments
This work was supported by Institute of Eco-Chongming (ECNU-I-EC20201).

References
Asaf, D., Pedersen, D., Matveev, V., Peleg, M., Kern, C., Zingler, J., et al. (2009). Long-term measurements of NOx radical at a semi-arid urban site: 1. Extreme concentration events and their oxidation capacity. Environmental Science & Technology, 43(24), 9117–9123. https://doi.org/10.1021/es900798b
Bo, Y., Cai, H., & Xie, S. D. (2008). Spatial and temporal variation of historical anthropogenic NMVOCs emission inventories in China. Atmospheric Chemistry and Physics, 8(23), 7297–7316. https://doi.org/10.5194/acp-8-7297-2008
Booher, N. L., Marshall, J. D., Alvarez, S., Chance, K. V., Fried, A., Kurosu, T. F., et al. (2011). Formaldehyde columns from the ozone monitoring instrument: Urban versus background levels and evaluation using aircraft data and a global model. Journal of Geophysical Research, 116, 11. https://doi.org/10.1029/2010jd014870
Chang, Y., Zhang, Y., Tian, C., Zhang, S., Ma, X., Cao, F., et al. (2018). Nitrogen isotope fractionation during gas-to-particle conversion of NOx to NO3− in the atmosphere—implications for isotope-based NOx source apportionment. Atmospheric Chemistry and Physics, 18(16), 11647–11661. https://doi.org/10.5194/acp-18-11647-2018
Cheng, X., Ma, J., Jin, J., Guo, J., Liu, Y., Peng, J., et al. (2020). Retrieving tropospheric NOx vertical column densities around the city of Beijing and estimating NOx emissions based on car MAX-DOAS measurements. Atmospheric Chemistry and Physics, 20(17), 10757–10774. https://doi.org/10.5194/acp-20-10757-2020
Dai, Q., Liu, B., Bi, X., Wu, J., Liang, D., Zhang, Y., et al. (2020). Dispersion normalized PMF provides insights into the significant changes in source contributions to PM2.5 after the COVID-19 Outbreak. Environmental Science & Technology, 54(16), 9917–9927. https://doi.org/10.1021/acs.est.0c02776
Dimitropoulou, E., Hendrick, F., Finardi, G., Friedrich, M. M., Merlaud, A., Tack, F., et al. (2020). Validation of TROPOMI tropospheric NO2 columns using dual-scan multi-axis differential optical absorption spectroscopy (MAX-DOAS) measurements in Uccle, Brussels. Atmospheric Measurements Techniques, 13(10), 5165–5191. https://doi.org/10.5194/amt-13-5165-2020
Duncan, B. N., Yoshida, Y., Olson, J. R., Sillman, S., Martin, R. V., Lamsal, L., et al. (2010). Application of OMI observations to a space-based indicator of NOx and VOC controls on surface ozone formation. Atmospheric Environment, 44, 2213–2223. https://doi.org/10.1016/j.atmosenv.2010.03.010
Eskes, H. J., Eichmann, K.-U. E., Lambert, J.-C., Loyola, D., Veefkind, J. P., Dehn, A., & Zehner, C. (2020). SSP mission performance center nitrogen dioxide [L2 NO2____] readme. Retrieved from https://sentinel.esa.int/documents/247904/3541451/Sentinel-5P-Nitrogen-Dioxide-Level-2-Product-Readme-File
Fang, X., Park, S., Saito, T., Tunnicliffe, R. J., Ganesan, A. L., Rigby, M., et al. (2019). Rapid increase in ozone-depleting chloroform emissions from China. Nature Geoscience, 12(2), 89–93. https://doi.org/10.1038/s41561-018-0278-2
Feng, T., Zhao, S., Bei, N., Wu, J., Liu, S., Li, X., et al. (2019). Secondary organic aerosol enhanced by increasing atmospheric oxidizing capacity in Beijing-Tianjin-Hebei (BTH), China. Atmospheric Chemistry and Physics, 19(11), 7429–7443. https://doi.org/10.5194/acp-19-7429-2019
Feng, T., Zhao, S., Zhang, X., Wang, Q., Liu, L., Li, G., & Tie, X. (2020). Increasing wintertime ozone levels and secondary aerosol formation in the Guanzhong basin, central China. The Science of the Total Environment, 745, 140961. https://doi.org/10.1016/j.scitotenv.2020.140961
Geyer, A., Alicke, B., Konrad, S., Schmitz, T., Stutz, J., & Platt, U. (2001). Chemistry and oxidation capacity of the nitrate radical in the continental boundary layer near Berlin. Journal of Geophysical Research, 106(D8), 8013–8025. https://doi.org/10.1029/2000jd000681
Goldstein, A. H., & Galbally, I. E. (2007). Known and unexplored organic constituents in the earth’s atmosphere. Atmospheric Chemistry and Physics, 8, 1514–1521. https://doi.org/10.5194/acp-8-1514-2008
Griffith, S. M., Huang, W.-S., Lin, C.-C., Chen, Y.-C., Chang, K.-E., Lin, T.-H., et al. (2020). Long-range air pollution transport in East Asia during the first week of the COVID-19 lockdown in China. The Science of the Total Environment, 741, 140214. https://doi.org/10.1016/j.scitotenv.2020.140214
Hsiang, S. L., Allen, D., Annan-Phan, S., Bell, K., Bolliger, I., Chong, T., et al. (2020). The effect of large-scale anti-contagion policies on the COVID-19 pandemic. Nature, 584, 262–267.
Hu, J., Li, X., Huang, L., Ying, Q., Zhang, Q., Zhao, B., et al. (2017). Ensemble prediction of air quality using the WRF/CMAQ model system for health effect studies in China. Atmospheric Chemistry and Physics, 17(21), 13103–13118. https://doi.org/10.5194/acp-17-13103-2017
Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., et al. (2020). Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. National Science Review, 8(2), nzaa.137.
Ialongo, I., Virta, H., Eskes, H., Hovila, J., & Dourou, J. (2020). Comparison of TROPOMI/Sentinel-5 Precursor NO2 observations with ground-based measurements in Helsinki. Atmospheric Measurements Technique, 13(1), 205–218. https://doi.org/10.5194/amt-13-205-2020
Jimenez, P., & Baldasano, J. M. (2004). Ozone response to precursor controls in very complex terrains: Use of photochemical indicators to assess O-3-N0x-VOC sensitivity in the northeastern Iberian Peninsula. Journal of Geophysical Research, 109(D20). https://doi.org/10.1029/2004jd004985
Zhang, Q., Yuan, B., Shao, M., Wang, X., Lu, S., Lu, K., et al. (2014). Variations of ground-level O3 and its precursors in Beijing in summertime between 2005 and 2011. *Atmospheric Chemistry and Physics,* 14(12), 6089–6101. https://doi.org/10.5194/acp-14-6089-2014
Zhao, K., Luo, H., Yuan, Z., Xu, D., Du, Y., Zhang, S., et al. (2021). Identification of close relationship between atmospheric oxidation and ozone formation regimes in a photochemically active region. *Journal of Environmental Sciences,* 102, 373–383. https://doi.org/10.1016/j.jes.2020.09.038
Zhao, Y., Zhang, K., Xu, X., Shen, H., Zhu, X., Zhang, Y., et al. (2020). Substantial changes in nitrogen dioxide and ozone after excluding meteorological impacts during the COVID-19 outbreak in Mainland China. *Environmental Science and Technology Letters,* 7(6), 402–408. https://doi.org/10.1021/acs.estlett.0c00304

References From the Supporting Information

Emery, C., Tai, E., & Yarwood, G., & International Corp. (2001). Enhanced meteorological modeling and performance evaluation for two texas episodes, paper presented at In: Report to the Texas Natural Resources Conservation Commission. Novato, CA. p.b.E.
EPA, U. (2005). Guidance on the use of models and other analyses in attainment demonstrations for the 8-hour ozone. NAAQSRep. EPA-454/R-05-002.
EPA, U. (2007). Guidance on the use of models and other analyses for demonstrating attainment of air quality goals for ozone. *PM2.5,* and regional haze. US Environmental Protection Agency, Office of Air Quality Planning and Standards.
Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., & Wang, X. (2012). The model of emissions of gases and aerosols from nature version 2.1 (MEGAN2.1): An extended and updated framework for modeling biogenic emissions. *Geoscientific Model Development,* 5(6), 1471–1492.
Hu, J., Wang, P., Ying, Q., Zhang, H., Chen, J., Ge, X., et al. (2016). Modeling biogenic and anthropogenic secondary organic aerosol in China. *Atmospheric Chemistry and Physics,* 17(1), 77–92.
Huang, G., & Sun, K. (2020). Non-negligible impacts of clean air regulations on the reduction of tropospheric NO2 over East China during the COVID-19 pandemic observed by OMI and TROPOMI. *The Science of the Total Environment,* 745, 141023.
Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., & He, K. (2020). Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. EarthArXiv.
Liu, F., Page, A., Strode, S. A., Yoshida, Y., Choi, S., Zheng, B., et al. (2020). Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. *Science Advances,* 6(28), 5.
Ogen, Y. (2020). Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality. *Science of the Total Environment,* 726, 5.
Pei, Z., Han, G., Ma, X., Su, H., & Gong, W. (2020). Response of major air pollutants to COVID-19 lockdowns in China. *The Science of the Total Environment,* 743, 140879.
Shen, J., Zhao, Q., Cheng, Z., Wang, P., Ying, Q., Liu, J., et al. (2020). Insights into source origins and formation mechanisms of nitrate during winter haze episodes in the Yangtze River Delta. *The Science of the Total Environment,* 741.140187.
Sillman, S. (1995). The use of NOY, H2O2, and HNO3 as indicators for ozone-NOX-hydrocarbon sensitivity in urban locations. *Journal of Geophysical Research,* 100(D7), 14175–14188.
Veefkind, J. P., Aehn, I., McMullan, K., Forster, H., de Vries, J., Otter, G., et al. (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sensing of Environment,* 120, 70–83.
Wang, P., Chen, Y., Hu, J. L., Zhang, H. L., & Ying, Q. (2019). Attribution of tropospheric ozone to NOx and VOC Emissions: Considering ozone formation in the transition regime. *Environmental Science & Technology,* 53(3), 1404–1412.
Zhang, H., Li, J., Ying, Q., Yu, J. Z., Wu, D., Cheng, Y., et al. (2012). Source apportionment of PM2.5 nitrate and sulfate in China using a source-oriented chemical transport model. *Atmospheric Environment,* 62(62), 228–242.
Zhang, Y., Wen, X. Y., Wang, K., Vijayaraghavan, K., & Jacobson, M. Z. (2009). Probing into regional O3 and particulate matter pollution in the United States: 2. An examination of formation mechanisms through a process analysis technique and sensitivity study. *Journal of Geophysical Research,* 114, 31.