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Enhanced atmospheric oxidation capacity and associated ozone increases during COVID-19 lockdown in the Yangtze River Delta

Yu Wang,1, Shengqiang Zhu,1, Jinlong Ma,1, Juanyong Shen,b, Pengfei Wang,c, Peng Wang,d,⁎, Hongliang Zhang,a,e,⁎⁎

a Department of Environmental Science and Engineering, Fudan University, Shanghai 200438, China
b School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
c Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
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

• Enhanced atmospheric oxidation capacity is observed in the Yangtze River Delta during COVID-19 lockdown.
• NOx reduction is the reason for increases of oxidants (OH, HO2, and NO3).
• O3 is increased in the central Yangtze River Delta, corresponding to atmospheric oxidation capacity enhancement.

GRAPHICAL ABSTRACT

ABSTRACT

Aggressive air pollution control in China since 2013 has achieved sharp decreases in fine particulate matter (PM2.5), along with increased ozone (O3) concentrations. Due to the pandemic of coronavirus disease 2019 (COVID-19), China imposed nationwide restriction, leading to large reductions in economic activities and associated emissions. In particular, large decreases were found in nitrogen oxides (NOx) emissions (>50%) from transportation. However, O3 increased in the Yangtze River Delta (YRD), which cannot be fully explained by changes in NOx and volatile organic compound (VOCs) emissions. In this study, the Community Multi-scale Air Quality model was used to investigate O3 increase in the YRD. Our results show a significant increase of atmospheric oxidation capacity (AOC) indicated by enhanced oxidants levels (up to +25%) especially in southern Jiangsu, Shanghai and northern Zhejiang, inducing the elevated O3 during lockdown. Moreover, net P(HOx) of 0.4 to 1.6 ppb h−1 during lockdown (Case 2) was larger than the case without lockdown (Case 1), mainly resulting in the enhanced AOC and higher O3 production rate (+12%). This comprehensive analysis improves our understanding on AOC and associated O3 formation, which helps to design effective strategies to control O3.

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Action Plan was implemented in 2013 to improve air quality (Feng et al., 2019; Zheng et al., 2017). As fine particulate matter (PM$_{2.5}$) concentration is decreasing due to strict control measures (Geng et al., 2019; Zhang et al., 2018), ozone (O$_3$) concentration has an increasing trend (Chen et al., 2019; Wang et al., 2018), especially in populated and economically vibrant regions such as the Yangtze River Delta (YRD) (Ding et al., 2013; Shao et al., 2016; Xu et al., 2017). In recent years, the highest hourly O$_3$ frequently exceeded 160 μg/m$^3$ in the YRD (Li et al., 2019; Wang et al., 2019; Yang et al., 2020).

The sudden outbreak of the Coronavirus Disease 2019 (COVID-19) pandemic emerged significant social impacts in China (Atar and Atar, 2020; Nicola et al., 2020). To prevent the spread of COVID-19, a strict national lockdown was implemented since late January (Chinazzi et al., 2020; Tang et al., 2020). During the lockdown period, most transportation and commercial activities were terminated and almost all outdoor human activities were prohibited throughout the country, which gives an important opportunity to investigate the changes in air quality due to drastic emissions reduction. In the YRD, the alleviation of PM$_{2.5}$ was attributed to reduced emissions in the lockdown period (Huang et al., 2020), indicating that challenges exist in O$_3$ control. The increase of O$_3$ is likely due to complex non-linear processes in O$_3$ formation and changes in atmospheric oxidation capacity (AOC) (Kentarchos and Roelofs, 2003; Li et al., 2015; Tan et al., 2019b). Thus, this is a need to investigate the change of AOC during COVID-19 outbreak and its relationship with O$_3$ increase to help establish more effective strategies in controlling PM$_{2.5}$ and O$_3$ synergistically.

AOC is defined as the sum of individual oxidation rates of primary pollutants (such as volatile organic compounds, VOCs) by oxidants including hydrogen oxide radicals (HO$_x$ = OH + HO$_2$), and nitrogen oxide radical (NO$_3$) (Jacob, 2000; Monks, 2005; Singh et al., 1995). These oxidants are regarded as indicators to assess AOC, which determines characteristics of pollutants formation in the atmosphere (Geyer et al., 2001; Mao et al., 2010; Murray et al., 2014). In particular, hydroxyl radical (OH, major component of HO$_x$) plays important role in O$_3$ formation (Bloss et al., 2005; Sheehy et al., 2010). OH oxidizes VOCs to produce peroxy radicals, then peroxy radicals (such as HO$_2$) oxidize NO to produce NO$_2$ in competition with O$_3$ after NO$_2$ photolysis, leading to accumulation of O$_3$ (Fig. S1) (Pollack et al., 2013; Ren et al., 2013; Tan et al., 2019b).

Previous studies on AOC only focused on radical chemistry (Keywood et al., 2004; von Sonntag, 2007; Xue et al., 2016; Zheng et al., 2020). Limited studies have related to AOC changes with O$_3$ formation. Recent studies modeled the highest ever-reported concentrations of OH at urban site in the YRD (Zheng et al., 2020; Zhu et al., 2020), which indicates AOC is strong in this region. Therefore, it is necessary to study the changes of AOC due to NO$_x$ emission and O$_3$ elevation during the COVID-19 lockdown period.

In this study, we use the Community Multiscale Air Quality (CMAQ) model to investigate AOC characteristics and associated O$_3$ changes in the YRD during the COVID-19 lockdown. Major oxidants and their sources are also determined and analyzed. The study aims to conduct an in-depth analysis on correlation of AOC and O$_3$ in the YRD with implications for formulating effective O$_3$ control policy in future.

2. Materials and methods

2.1. Model application

CMAQ version 5.0.2 with modified SAPRC-11 photochemical mechanism (Carter and Heo, 2013; Ying et al., 2019) was applied to simulate gas pollutants from January 5 to February 29, 2020 that comprises the pre-lockdown (January 5 to 22) and lockdown (January 23 to February 29) periods. Two-level nested domains were used with horizontal resolutions of 36-km and 12-km, respectively. The 36-km (197 × 127 grid cells) domain covered most of East Asia and the 12-km (97 × 88) domain included the YRD (Fig. S2).

The Weather Research and Forecasting model (WRF) v3.6.1 was utilized to generate meteorology inputs to CMAQ with initial and boundary conditions from National Centers for Environmental Prediction (NCEP) FNL Operational Model Global Tropospheric Analyses dataset (NCEP, 2000; Zhang et al., 2012). The anthropogenic emissions were from Multi-resolution Emission Inventory for China (MEIC) for 2016 (http://www.meicmodel.org). Biogenic emissions were generated using the Model of Emissions of Gases and Aerosols from Nature v2.1 (Guenther et al., 2012).

2.2. Emission scenarios

Two simulation scenarios were performed in this study, with the business as usual case (Case 1) using unchanged emission and Case 2 adopting reduced emissions in the lockdown period. The decreases of emissions during lockdown were based on Huang et al. (2020). Provincal changes were made to carbon monoxide (CO, >13%), NO$_2$ (>45%), sulfur dioxide (SO$_2$, >20%), VOCs (>30%), and PM$_{2.5}$ (>15%). NO$_2$ levels declined the most during lockdown as transportation is the major source. Table 1 shows the detailed reduction ratios for each province in the YRD. By comparing the two cases, the impacts of reduced anthropogenic emissions on AOC and O$_3$ concentrations were evaluated.

2.3. Determining sources and sinks of oxidants

Quantifying contributions of individual processes to atmospheric oxidants provides a fundamental explanation and identifies key oxidants chemical characteristics related to AOC. Previous AOC studies have generally used box model to determine the sources and sinks of HO$_x$. (Tan et al., 2017; Tan et al., 2019b; Zhu et al., 2020), which was constrained to observations of photolysis frequencies, long-lived trace gases, and meteorological parameters. And in this study, we used the CMAQ model. The process analysis technique in CMAQ was used, which includes integrated process rate (IPR) analysis and integrated reaction rate analysis (IRR) (https://www.cmascenter.org/cmaq/science_documentation/pdf/ch16.pdf) (Arshadi and Rajaram, 2015; Liu et al., 2010). The IRR analysis was directly computed from reaction rates at the beginning and end of each chemistry integration time step. Radical initiation reactions are almost always photolytic reactions that generate new radicals. The termination reactions remove radicals through the formation of stable products.

The budgets of HO$_x$ including OH and HO$_2$ were evaluated quantitatively, aiming to identify the characteristics of AOC. In the radical production process, the major sources of HO$_x$ and HO$_2$ are photolysis reactions involving nitrous acid (HONO), O$_3$, and formaldehyde (HCHO) and the reactions of O$_3$ with alkenes. In radical loss process, reactions that forms stable compounds such as $\text{OH} + \text{HO}_2 = \text{H}_2\text{O}_2$ are considered. The detailed process of HO$_x$ budget are shown in Table 2 that modified from Tan et al. (2019b). It should be noted that this study only considers chemical processes in the budget analysis, while physical processes such as deposition and transport are not included.

| Species | Province | NO$_x$ | SO$_2$ | VOC | PM | CO | BC | OC |
|---------|----------|--------|--------|-----|----|----|----|----|
| Reduction factors | Shanghai | 48% | 42% | 45% | 34% | 35% | 54% | 42% |
| | Jiangsu | 50% | 26% | 41% | 16% | 23% | 35% | 7% |
| | Zhejiang | 50% | 29% | 45% | 30% | 41% | 49% | 20% |
| | Anhui | 56% | 22% | 31% | 11% | 14% | 22% | 4% |
| | Fujian | 51% | 30% | 42% | 19% | 29% | 31% | 7% |
| | Henan | 57% | 22% | 41% | 18% | 23% | 35% | 8% |
| | Shandong | 50% | 25% | 39% | 19% | 23% | 35% | 9% |

Table 1 Emission reduction factors for Case 2 during the lockdown period in this study. The scaling factors are from Huang et al. (2020).
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2.4. $O_3$–$NO_x$–VOC sensitivity

The type of $O_3$ sensitivity regime is critical for the formation of $O_3$. Transition regime, $NO_x$-limited regime and VOC-limited regime have been demonstrated to explain the formation of $O_3$. At $NO_x$-limited regime (low $NO$ conditions), VOCs are more competitive than $NO_x$ to react with $OH$. The main reaction of VOCs and $OH$ can produce peroxy radicals, leading to the $O_3$ concentration increase. At VOC-limited regimes (high $NO$ conditions), the high levels NO can consume $O_3$ and suppress the accumulation of $O_3$ (named the “titration effect”) (Chou et al., 2006). Here the ratio of $R$ (defined as $R_{HONO}$) has been adopted to evaluate the $O_3$ production sensitivity, where $P_{HONO}$ is the formation rate of hydrogen peroxide ($H_2O_2$), and $P_{NOx}$ is the formation rate of nitric acid ($HNO_3$). And we take $R < 0.35$ as indicating VOC-limited regime, and $R > 0.35$ as $NO_x$-limited regime (M liford et al., 1994; Sillman et al., 1995). The spatial distributions of $R$ reveal the characteristics of $O_3$ formation over the study area.

3. Results and discussions

3.1. WRF-CMAQ model validation

Meteorological conditions were validated against available observation data (~200 stations) from the National Climate Data Center (NCDC) (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-lit, last access August 2020) (Table S1). Temperature (T2) and wind speed (WS) were slightly overpredicted, indicating by positive mean bias (MB) values. MB values of wind direction was within benchmarks suggested by Emery and Tai (2001), while gross error (GE) values exceeded the benchmarks slightly. In general, WRF shows acceptable performance that is similar to previous studies over China (Hong et al., 2017; Hu et al., 2016; Hu et al., 2017).

CMAQ simulations were validated by comparing prediction with hourly observations from China National Environmental Monitoring Center (https://quotssoft.net/air, last access August 2020) (Table S2). Predicted $O_3$ (both 0–1 h and 0–8 h) and $PM_{2.5}$ were within the criteria suggested by US EPA with slightly overestimation (EPA, 2007). In three representative cities of YRD (Nanjing, Shanghai, and Hangzhou), predicted $O_3$ agreed well with observation, with MB values of $−0.03$ to 0.01 (Fig. S3). The model performance is acceptable for $NO_2$ in Shanghai, while for Hangzhou and Nanjing, the model trend is the same, but there is a significant overestimation, which could be related to the inventory adjustment ratio in Zhejiang Province and Jiangsu Province (Fig. S4). Overall, CMAQ model gives robust results for following analysis.

3.2. Changes in AOC

3.2.1. Enhanced AOC in the YRD during the lockdown

During the COVID-19 lockdown, elevated AOC was predicted in Case 2 with emission reductions in large areas of the YRD, indicating by increased oxidants of $OH$, $HO_2$, and $NO_3$ (Fig. 1). Compared to Case 1, elevated $OH$ and $HO_2$ in Case 2 occurred in most areas especially in Jiangsu, Shanghai and larger area of Zhejiang (Fig. 1c and f), with the growth rate of 15–20% and 10–25%, respectively. $HO_2$ showed increases in similar regions (Fig. 1i) with less sink due to sharply reduced $NO_x$ concentrations (Fig. S5c) (Atkinson et al., 2004; Jacob, 2000; Monks, 2005). Similarly, elevated $NO_3$ occurred in Jiangsu, Shanghai and northern Zhejiang (Fig. 11) with highest increase of 17%, mainly due to reduced reactions with VOCs in $HO_2$ and RO2 production reactions ($NO_2 + $alkenes $\rightarrow$ $HO_2/RO_2 + $products, Fig. S6c) (Dentener and Crutzen, 1993; Fry et al., 2009; Rudich et al., 1998). $NO_3$ level showed a decrease by 15% in the southern Zhejiang during the lockdown, mainly due to declining $O_3$ and $NO_2$ (Fig. 4c and Fig. S5c) as the largest sources of $NO_2$ ($O_3 + NO_3$) in Shanghai, Jiangsu and northern Zhejiang, and 2–10% declines in southern Zhejiang.

Averaged diurnal variations of major oxidants in three major cities (Nanjing, Shanghai and Hangzhou) are shown in Fig. 2. For $HO_2$, the peak values were observed at noontime, while, as the dominate oxidant in the nighttime, the higher levels of $NO_3$ occurred at the night. During the COVID-19 lockdown, elevated AOC was predicted in the Case 2 in three major cities, indicating by the rising major oxidants ($OH$, $HO_2$, and $NO_3$). Compared to Case 1, the daytime $HO_2$ and nighttime $NO_3$ peak values were increased by 33–78% (50–78% in Nanjing, 33–50% in Shanghai, and 40–49% in Hangzhou) and 50–64% (50% in Nanjing and Hangzhou, and 64% in Shanghai), respectively. The $HO_2$ peak value were the highest in Hangzhou (0.14 ppt for $OH$ and 5.2 ppt for $HO_2$) in Case 2, followed by Nanjing (0.12 ppt for $OH$ and 3.2 ppt for $HO_2$) and Shanghai (0.12 ppt for $OH$ and 3 ppt for $HO_2$), which were consist with the average net $P(HO_2)$ for three major cities ($−0.0688$ ppb h$^{−1}$ in Nanjing, $−0.0602$ ppb h$^{−1}$ in Shanghai, and $−0.0368$ ppb h$^{−1}$ in Hangzhou, see Sect 3.2.2). Similarly, the $NO_3$ peak value was the highest in Hangzhou (3.1 ppt) in Case 2, followed by Nanjing and Shanghai (2.2 ppt), demonstrating the higher AOC level in three major cities during the COVID-19 lockdown period especially in Shanghai.

Table 2

| Chemical reactions considered in the radical budget analysis of $OH$ and $HO_2$. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Product of $HO_2$ | $HO_2 + h\nu$ | $HO_2 + h\nu$ (<400 nm) | $OH + NO$ | $O(D) + H_2O \rightarrow OH + OH$ | $HCHO + h\nu$ (<305 nm) + $2O_2$ | $2HO_2 + CO$ |
| Loss of $HO_2$ | $OH + NO_2$ | $OH + NO_2 \rightarrow HNO_3$ | $HONO + h\nu$ | $OH_2 + HO_2 \rightarrow H_2O + O_2$ | $HO_2 + H_2O + H_2O + O_2$ | $HO_2 + RO_2 \rightarrow ROOH + O_2$ |
| $R_{HONO}$ | $R_{NOx}$ | $R_{NOx}$ | $R_{NOx}$ | $R_{NOx}$ | $R_{NOx}$ | $R_{NOx}$ |

2.2. $HO_2$ budget

Quantifying the production and loss rates of $HO_2$ ($P(HO_2)$ and $L(HO_2)$) is crucial to understand the increase of AOC during the lockdown. The sources and sinks of $HO_2$ in three major cities are shown in Fig. 3. From both Case 1 and Case 2, $P(HO_2)$ was dominated by photolysis reaction involving $O_3$, $HONO$, and $HCHO$. The photolysis of $HONO$ (28%–52%, Table 2R1), followed by $HCHO$ (15%–25%, Table 2R3) and $O_3$ (8%–20%, Table 2R2) for the three cities in Case 1 (Fig. 3a–c). And the ozoneolysis of alkenes (Table 2R4) contributed 15%–25% during daytime and is the only primary source considered here at night. In addition, total $P(HO_2)$ declined in Case 2 compared to Case 1 (Fig. 3), which was mainly attributed to the lower $L(HO_2)$ rates. However, due to increase in $O_3$ concentrations (Fig. 4d–f), the enhanced ozonolysis of alkenes (0–0.2 ppb h$^{−1}$, Fig. S7) in all these cities were found in Case 2 at night. In Case 2, $P(HO_2)$ was dominated by photolysis of $O_3$ and $HONO$ (both 25%–42%) and $HONO$ (18%–35%) for the three cities. Also, in Case 2, the reaction of $O(D) + H_2O$ produced OH rates were up to 0.3 ppb h$^{−1}$ in Shanghai at noontime, which is lower than that reported by Tan et al. (2019b) (1.4 ppb h$^{−1}$), due to the relatively low $O_3$ in winter (up to 56 ppb around noontime, Fig. 4d). In Shanghai, $HCHO$ produced $HO_2$ rate was up to 0.2 ppb h$^{−1}$ (Case 2), which was lower than previous studies (0.8 ppb h$^{−1}$) (Tan et al., 2019b; Zhtu et al., 2020). The rates of $HONO$ producing $OH$ were (up to 0.2 ppb h$^{−1}$ for Case 2) slightly lower than previous studies (up to 0.38 ppb h$^{−1}$) (Tan et al., 2019b; Wang et al., 2014; Zhtu et al., 2020), which could be attributed to the absence of anthropogenic source emissions of $HONO$ resulting in a lower $HONO$ (Fig. S8). The ozoneolysis of alkenes producing $HO_2$ (−0.18 ppb h$^{−1}$ averagely) are consistent with previous studies.

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The lower L(HOx) rates were found in Case 2 in all these cities, mainly due to a large decrease in NOx (Fig. S5c) during the lockdown. From both Case 1 and Case 2, L(HOx) was dominated by the reaction of OH + NO2 (about 98%, Table 2 R5), followed by the reaction of HO2 + H2O2 (2%, Table 2 R6). The HOx losses via NOx radical reactions were much larger than that of radical-radical reactions such as HO2 + H2O2 (0.01–0.08 ppb h\(^{-1}\), Table 2 R6-R8) for all the three cities, indicating a high-NOx chemistry environment in the YRD. Consequently, total L(HOx) declined significantly in Case 2 compared to Case 1 mainly due to the lower (30%–40%) NOx emissions (Fig. S5). HOx losses via NOx−radical reactions were decreased 36% (up to 0.85 ppb h\(^{-1}\)), by 30% (up to 0.7 ppb h\(^{-1}\)), and 37% (up to 0.75 ppb h\(^{-1}\)) in Shanghai, Nanjing, and Hangzhou, respectively (Fig. S9).

As shown in Fig. S9, there was an imbalance between P(HOx) and L(HOx) rates (the net P(HOx) = P(HOx) - L(HOx)) from both Case 1 and Case 2. Compared with Case 1, the net P(HOx) was more significant in Case 2 ranging from −0.4 ppb h\(^{-1}\) to 1.6 ppb h\(^{-1}\), mainly resulting in the enhanced AOC in the YRD during the lockdown. From the late afternoon until nighttime, the higher L(HOx) (0.1 ppb h\(^{-1}\)) was observed compared to P(HOx) from both cases. Similar uncertainties are also reported in Tan et al. (2019a), which could due to the exclusion of physical processes such as transport and depositions in the budget analysis.

### 3.3. Impacts of oxidants on O3 formation

O3 concentration during the lockdown was up to 12% higher in economically developed areas in comparison to Case 1, especially in southern Jiangsu, Shanghai and northern Zhejiang (Fig. 4a–c), consisting with elevated AOC in these areas. In major cities, the important increase in O3 was found at noontime in Case 2, which is consistent with changes of...
OH, the dominant oxidant (Fig. 4d–f). The diurnal variations of P(HOx) and L(HOx) further revealed the impacts of oxidants on O3. In Case 2 the net P(HOx) was increased during nighttime (Fig. S7), implying that enhanced AOC increased O3.

Meteorological conditions and changes in O3 sensitivity regime could also be the reasons for O3 increases (Sitnov, 1996; Tuck and Hovde, 1999; Wang et al., 2017a; Wang et al., 2017b; Wang et al., 2009). Further analysis was conducted to identify their roles. A slight increase in temperature during the lockdown period was observed (Fig. S10), which may play a role in increased O3. Wind fields (Fig. S11) and relative humidity (Fig. S10) remained unchanged in comparison to pre-lockdown. As for O3 sensitivity, the spatial distributions revealed the characteristics of O3 formation over the YRD using an indicator (defined as $\frac{P_{\text{NOx}}}{P_{\text{O}}}$) (Milford et al., 1994; Sillman et al., 1995). In the Case 1, VOC-limited regime mainly occurred in urban areas of Shanghai, southern Jiangsu, and Zhejiang, while NOx-limited regime tended to be distributed over suburban areas. Compared to Case 1, Case 2 was indicative of noticeable changed from VOC-limited regimes to NOx-limited regimes in eastern parts of Shanghai, southern Jiangsu, and northern Zhejiang (Fig. 4i). These areas were characterized by dramatical decline of NOx emissions from mobile vehicles during the lockdown period, where O3 increased significantly (Fig. 4c). The low levels NOx can enhance AOC and further promote the accumulation of O3 as discussed in section 3.2.1. VOC-limited regimes were mainly found in developed
urban regions such as most of southern Jiangsu in Case 2. In these regions (except for southern Zhejiang), the rising O₃ occurred during the lockdown, which is induced from the higher AOC in spite of the lower VOCs emissions. Therefore, elevated AOC can be deduced as the main contributor to elevated O₃ in YRD during the COVID-19 lockdown periods.

4. Conclusions

In this paper, oxidants and O₃ were simulated before and during the COVID-19 lockdown in the YRD using WRF/CMAQ modeling system with modified anthropogenic emissions. Results showed that the dramatic reductions in NOₓ (>50%) led to up to 15–20%, 10–25%, and 17% increases of OH, HO₂, and NO₃ in Jiangsu, Shanghai, and northern Zhejiang during the lockdown period, respectively. Similarly, O₃ level was higher (up to 12%) in these regions during the lockdown period, consisting with changes of AOC. During the lockdown period, total P(HOₓ) declined significantly in Case 2, compared with Case 1. In contrast, the ozonolysis of alkenes process increased at night (up to 0.2 ppb h⁻¹) due to increase in O₃ concentration. Total L(HOₓ) declined significantly in Case 2, resulting from large reductions in NOₓ emissions. The enhanced AOC was mainly attributed to the higher net P(HOₓ) rates in the YRD. For three typical urban cities (Nanjing, Shanghai, and Hangzhou) in Case 2, P(HOₓ) was dominated by photolysis of O₃ and HONO (both 25%–42%) and HONO (18%–35%). While the reaction of OH + NO₂ is the most important contributor to L(HOₓ) (about 98%), followed by the reaction of HO₂ + HO₂.
Currently, O3 pollution becomes the major air quality challenge in the YRD region while PM2.5 concentrations has decreased in the recent decade. To mitigate O3 pollution, more localized and stringent policies especially on controlling VOCs emissions should be implemented. This study also suggests the urgent need for a deep understanding of radical chemistry and AOC, so as to design more effective control strategies in the YRD.

CRediT authorship contribution statement

Yu Wang: Investigation, Visualization, Writing – original draft. Shengqiang Zhu: Methodology, Investigation, Writing – review & editing. Jinlong Ma: Methodology, Visualization. Juanyong Shen: Methodology, Investigation. Pengfei Wang: Investigation. Peng Wang: Methodology, Writing – review & editing. Hongliang Zhang: Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Fig. 4. (a–c) Spatial distribution of simulated MDA8 O3 concentrations before and during COVID-19 lockdown period. (d–f) Averaged diurnal variations of modeled O3 concentrations in three major cities (Purple squares represent the three weeks before COVID-19 outbreak, yellow squares represent Case 1 in COVID-19 lockdown, and green squares represent Case 2 in COVID-19 lockdown). (g–i) Spatial distributions of O3 production sensitivity before and during COVID-19 lockdown.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144796.

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