Impact of COVID-19 on air quality in the Yangtze River Delta, China

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Abstract To investigate the effect of nationwide restrictions due to COVID-19 on air quality in the Yangtze River Delta (YRD), China, we defined four periods named period I (January 1 to 23, 2020), period II (January 24 to February 23), period III (February 24 to April 7), and period IV (April 8 to May 31), which indicated normal period, lockdown period, regional work resumption period, and nationwide work resumption period, respectively. Hourly $PM_{2.5}$, PM_{10} , NO_2 , SO_2 , CO , and O_3 in 41 cities in the YRD region were analyzed. Compared to period I, NO_2 decreased by 58% during period II and increased in periods III and IV. SO_2 remained constant during the four periods ($7\text{--}8\text{ }\mu\text{g}/\text{m}^3$). Higher $PM_{2.5}$ concentration was monitored during period II ($41\text{ }\mu\text{g}/\text{m}^3$) when compared to period III ($35\text{ }\mu\text{g}/\text{m}^3$), which was resulted from the enhanced secondary formation. Spatial distribution analysis further indicated that $PM_{2.5}$ in the northern YRD during period II was higher than that during period III, whereas $PM_{2.5}$ in the southern YRD in the period II was similar to that in period III. The results demonstrated that $PM_{2.5}$ shows a nonlinear response to the reduction of its precursors, and

this phenomenon varies in different areas. Compared to periods I ($36\text{ }\mu\text{g}/\text{m}^3$) and III ($64\text{ }\mu\text{g}/\text{m}^3$), relatively higher O_3 during period II ($64\text{ }\mu\text{g}/\text{m}^3$) was probably resulted from less NO emission and hence weakened NO titration effect. The study suggested that coordinated and balanced measures are needed to improve air quality.

Keywords Coronavirus · NO_2 · $PM_{2.5}$ · Spatiotemporal variation · Yangtze River Delta

Introduction

The ongoing outbreak of COVID-19 has attacked 216 countries and areas, causing more than 16 million confirmed cases and 655,112 deaths globally as of 29 July 2020 (WHO, 2020). The outbreak of COVID-19 in China occurred after the Chinese Spring Festival (Festival) which was featured by high-intensity population mobility. Before the festival, numerous migrant residents come back to their hometowns to celebrate family reunions and return to the city for school and work after the holiday (Yao et al., 2019). For example, the migrant population across provinces in the Yangtze River Delta (YRD) region accounted for 71.7% in 2017 (National Health Commission of the People's Republic of China, 2019). COVID-19 is transmitted through human respiratory droplets, direct contact, and even aerosol transmission (Liu et al.,

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2020). To control the movement of its population to avoid infection after the 2020 Festival, China implemented nationwide restrictions. For example, the traditional 7-day festival was extended to 18 days (from January 24 to February 10). Besides, 14 days of quarantine was required after people return to their working and living cities and schools closed. Thus, COVID-19 caused large-scale and prolonged shutdowns in urban areas, leading to a large reduction of the primary emission.

The effectiveness of anthropogenic emission reduction on air quality has been a concerning issue for researchers. Previous studies investigated the role of short-term pollutant emission control measures in air quality improvement during the 2008 Beijing Olympics (8–24 August, Wang et al., 2010; Witte et al., 2009), the 2010 Guangzhou Asian Games (12–27 November, Liu et al., 2013; Tao et al., 2015; Yao et al., 2013), the 2014 Asia-Pacific Economic Cooperation (APEC) meeting (5–11 November, Guo et al., 2016; Tang et al., 2015; Xu et al., 2019), and the 7-day festival (Huang et al., 2012; Jiang et al., 2015; Yao et al., 2019). The COVID-19 provided a unique chance to test the sensitivity of primary emission reduction on air quality (Huang et al., 2020; Zhang et al., 2020; Zheng et al., 2020). Zheng et al. investigated the variations in chemical compositions, source contributions, and regional transport of $PM_{2.5}$ from January 23 to February 22, 2020, compared with the same period in 2019 (Zheng et al., 2020). Zhang et al. reported NO_x emission reduction and recovery during COVID-19 in East China from January 1 to March 12, 2020 (Zhang et al., 2020). Huang et al. investigated the haze formation mechanism in the case of a reduction of primary emissions in East China from January to February 2020 (Huang et al., 2020). As the COVID-19 infection continues, studies of its impact on air quality on longer time scales are desirable.

The YRD region is severely affected by the epidemic. For example, the Shanghai government listed Hubei Province and another 19 cities as severely affected areas in China, among which 9 cities are located in the YRD region (<https://www.shaimaiba.com/baike/shenghuo/18068.html>). This study investigated the effects of COVID-19 on air quality based on 5 months of hourly concentration of $PM_{2.5}$, PM_{10} , NO_2 , SO_2 , CO , and O_3 in 41 cities in the YRD region. Spatial-temporal variation and daily pattern of air pollutants and comparison of changes in 2019 were discussed.

Methods

Monitoring datasets

Hourly concentrations of $PM_{2.5}$, PM_{10} , NO_2 , SO_2 , CO , and O_3 in 41 cities of the YRD from January 1, 2020 to May 31, 2020 were obtained from the National Urban Air Quality Real-Time Publishing Platform (<http://106.37.208.233:20035/>) of China National Environmental Monitoring Centre. Each city was equipped with several air quality automatic monitoring stations (urban assessing stations). Some cities with special geographical location were additionally equipped with one regional assessing stations (marked as Duizhaodian on the Platform). Hourly concentrations of pollutants in each city were averaged from all the monitoring stations except the regional assessing stations (Duizhaodian). Hourly mean concentrations of pollutants of YRD region were averaged from those of the 41 cities. The 41 cities include 13 cities in Jiangsu Province, 11 cities in Zhejiang Province, 16 cities in Anhui Province, and Shanghai.

Important time nodes

To investigate the effects of reduced anthropogenic activities as COVID-19 on air quality, we divided the whole study period as four specific periods based on three important time nodes. On January 23, Wuhan, the first place of the outbreak of coronavirus, declared unprecedented traffic restrictions, including suspending the city's public transport and all outbound flights and trains. This event marked the beginning of lockdown in China. Shanghai, the leading city of the YRD region, announced that work resumption should not be earlier than February 9. It needs to be emphasized that most people have left the city before January 23 to return to their hometown for the Chinese Spring Festival (started from January 24), called as "Chunyun." Home quarantine is required for 14 days after they return to Shanghai before work resumption. Thus, the lockdown period lasted from January 24 to February 23. From February 24, massive resumption of work and production in urban areas were started in the YRD region. On 00:00, April 8, Wuhan started lifting outbound travel restrictions, which indicated ending lockdown all over China. Thus, the four periods

were from January 1 to 23, January 24 to February 23, February 24 to April 7, and April 8 to May 31, which were sequentially numbered as I, II, III, and IV, respectively, as seen in Fig. 1.

In period I, a few daily cases were reported and scarce containment measure was taken, which was considered as a normal period. On the contrary, the COVID-19 outbreak occurred during period II, and the most rigorous control measurements were implemented to reduce population mobility. In period III, almost no locally transmitted infections were recorded and the reported cases were sourced from virus carriers traveling from abroad. People started to resume work and normal life in YRD during this period. The domestic coronavirus is effectively under control in China during period IV, and this period represents a nationwide resumption of work and production. In summary, period I, period II, period III, and period IV represent pre-lockdown period, lockdown period, period of ending lockdown on urban scale, and period of ending lockdown on a national scale, respectively.

Processing of meteorological data

The original meteorological data is from the ERA5 reanalysis datasets (ERA5 hourly data on single levels from 1979 to present), which is provided by the

European Centre for Medium-Range Weather Forecasts (ECMWF). Variables including precipitation, total column water vapor, 10-m u-component of wind, and 10-m v-component of wind were used in the present work, with horizontal resolution of $0.25^\circ \times 0.25^\circ$. The ERA5 atmospheric reanalysis was reported to have improved performance (Graham et al., 2019).

Results

Overview of air quality

The average concentrations of air pollutants in YRD during the four periods are depicted in Fig. 2. NO_2 , a primary pollutant from vehicle emission, presented the highest concentration during period I and significantly decreased during period II and then increased during periods III and IV, with concentrations of 39, 16, 29, and 26 $\mu\text{g}/\text{m}^3$ during the four sequential periods, respectively. Independent-sample *T* test was applied to exam the significant difference in the mean value of NO_2 during the four periods. Results show that there are significant differences in the average NO_2 concentrations during period I, period II, and period III (both $P < 0.01$), and no significant difference in periods III and IV ($P > 0.05$). Compared to periods I and III, NO_2 decreased by 58% during

Fig. 1 Daily increases in new confirmed cases of COVID-19 in the Yangtze River Delta (YRD) region, China. I, II, III, and IV indicate period I (from January 1 to 23), period II (from January 24 to February 23), period III (February 24 to April 7), and period IV (April 8 to May 31). Source: (Jiangsu

Commission of Health, 2020; Health Commission of Zhejiang Province, 2020; National Health Commission of the People's Republic of China, 2020; Shanghai Municipal Health Commission, 2020)

Fig. 2 Statistics of the concentrations of NO_2 , $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO , and O_3 during the four periods

period II and increased by 81% during period III. However, $\text{PM}_{2.5}$, mainly formed from secondary formation, did not exhibit such a variation trend. Concentrations of $\text{PM}_{2.5}$ during the four periods were 65, 41, 35, and 33 $\mu\text{g}/\text{m}^3$, respectively. *T* test indicated that $\text{PM}_{2.5}$ concentration in period II was significantly ($P < 0.01$) higher than that in periods III and IV. Despite lower primary emission of pollutants in period II, higher $\text{PM}_{2.5}$ indicated enhanced secondary formation (e.g. sulfate and nitrate) during period II, which was agreed well with the previous study (Chang et al., 2020; Huang et al., 2020). Huang et al.

(2020) measured major compositions of $\text{PM}_{2.5}$ (e.g., sulfate, nitrate, ammonium, and organic matter) during the COVID-2019 lockdown and provided evidence that the heavy haze pollution in East China during the lockdown was triggered by enhancements of secondary pollution. Chang et al. (2020) observed fast formation of secondary inorganic (mostly nitrate) aerosols in Shanghai during the 2020 Chinese Spring Festival (lockdown period) and highlighted that regional transport facilitated nitrate formation.

Unlike NO_2 , SO_2 , a primary pollutant mainly from industrial emission, exhibited no significant variation,

with concentrations of 8, 7, 7, and 8 $\mu\text{g}/\text{m}^3$ during the four periods. The latest study focusing on severe haze events characterized by high $\text{PM}_{2.5}$ concentration in China during COVID-19 outbreak proposed that large emission reduction in transportation and a slight reduction in industrial would not help avoid severe air pollution in China (Wang et al., 2020).

PM_{10} displayed a similar variation pattern to NO_2 , with concentrations of 79, 51, 59, and 61 $\mu\text{g}/\text{m}^3$ during periods I, II, III, and IV, respectively. Mass ratio of $\text{PM}_{2.5}/\text{PM}_{10}$ during the four periods was 82%, 81%, 61%, and 55%, respectively. A higher $\text{PM}_{2.5}/\text{PM}_{10}$ ratio in period II was consistent with the enhanced secondary formation during this period. CO concentrations were 0.952, 0.682, 0.633, and 0.625 mg/m^3 . Notably, O_3 exhibited a different variation trend from gaseous pollutants and particulate matters. Concentrations of O_3 were 36, 64, 64, and 93 $\mu\text{g}/\text{m}^3$ during the four periods. Compared to period I, O_3 increased by 77.8% during period II (64 $\mu\text{g}/\text{m}^3$). Huang et al. (2020) explained that large decreases in NO_x emissions increased O_3 and nighttime NO_3 radical formation, leading to increased atmospheric oxidizing capacity, which further facilitated the formation of secondary particulate matter.

Spatial-temporal variation

Figure 3 shows the daily variation of NO_2 , $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and O_3 in YRD during the four periods. Hourly NO_2 displayed a bimodal distribution during the four periods, with a morning peak and a nighttime peak. NO_2 at the nighttime peak (47 $\mu\text{g}/\text{m}^3$) was higher than that at the morning peak (40 $\mu\text{g}/\text{m}^3$) before the COVID-19 outbreak (period I), whereas NO_2 concentrations at the morning peak and nighttime peak were similar after the COVID-19 outbreak (periods II, III, and IV). $\text{PM}_{2.5}$ and PM_{10} presented a bimodal distribution during the four periods. Concentrations of $\text{PM}_{2.5}$ and PM_{10} at the nighttime peak were higher than that at the morning peak during period II. The gap between nighttime $\text{PM}_{2.5}$ concentration during period II and period III was greater than that in the daytime. However, $\text{PM}_{2.5}/\text{PM}_{10}$ ratios in the day (07:00–18:00, 86%, 86%, 62%, and 58%, respectively) were higher than that at night (19:00–06:00, 81%, 76%, 57%, and 49%, respectively) during the four periods, indicating stronger secondary formation in daytime. SO_2 exhibited a unimodal distribution during the four periods. However, the peak hour

Fig. 3 Daily patterns of NO_2 , $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and O_3 in the YRD during the four periods

when SO_2 showing the highest concentration differed. Compared to period II, the peak hour of SO_2 came earlier during periods III and IV. The results agreed well with the previous study conducted in Wuhan that the lockdown due to the COVID-19 outbreak modified the diurnal variation patterns of $\text{PM}_{2.5}$ sources (Zheng et al., 2020). CO presented a similar daily variation to $\text{PM}_{2.5}$, with relatively higher concentration during period II, compared to periods III and IV. O_3 exhibited similar daily variation during the four the periods, with a large peak at 15:00. The average O_3 concentrations during periods II and III were similar. However, nighttime O_3 during period II was higher than that in period III. A considerable level of nocturnal O_3 favors nocturnal NO_3 radical formation during period II (Sun et al., 2018).

Spatial variation of NO_2 , $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and O_3 in YRD during the four periods is depicted in Fig. 4. Nanjing, Hangzhou, and Hefei were provincial capital cities of Anhui, Jiangsu, and Zhejiang, respectively. Higher concentrations of NO_2 were observed in central YRD, including Shanghai, the provincial capital cities, and the adjacent cities during the four periods. In period I, NO_2 in central YRD were at the level of 40–60 $\mu\text{g}/\text{m}^3$. NO_2 concentrations in 33 cities (80%) decreased to less than 20 $\mu\text{g}/\text{m}^3$ during period II, among which included NO_2 in the southernmost three cities in YRD dropping to less than 10 $\mu\text{g}/\text{m}^3$. After the resumption of work and production, NO_2 in the central YRD increased to 30–40 $\mu\text{g}/\text{m}^3$. However, $\text{PM}_{2.5}$ exhibited a very different spatial distribution with NO_2 in the YRD. The highest average $\text{PM}_{2.5}$ concentrations (110–120 $\mu\text{g}/\text{m}^3$) were observed in the northern YRD, and $\text{PM}_{2.5}$ concentrations in the YRD shows a decreasing trend from north to south during period I. Higher $\text{PM}_{2.5}$ concentration was also measured in the northern part of the YRD during the period II, despite lower NO_2 in this area. $\text{PM}_{2.5}$ in northern YRD during period II was higher than that in periods III and IV, whereas $\text{PM}_{2.5}$ concentrations in southern YRD during periods II, III, and IV were similar. The spatial distribution of PM_{10} in the YRD was similar to $\text{PM}_{2.5}$, with a higher concentration in the northern YRD than that in the southern YRD during the four periods. However, increased PM_{10} in the southern YRD during periods III and IV was observed when compared to that in period II, which was different from $\text{PM}_{2.5}$. The difference in the

spatial and temporal distribution of $\text{PM}_{2.5}$ and PM_{10} indicated that road dust and construction dust are the main sources of PM_{10} in urban YRD.

Concentrations of SO_2 in the YRD displayed no significant difference in spatial variation during the four periods. SO_2 in most cities in the YRD were less than 10 $\mu\text{g}/\text{m}^3$, with SO_2 of a few cities ranging from 10 to 20 $\mu\text{g}/\text{m}^3$. This SO_2 level was still higher when compared to Barcelona, Spain (1.0–2.6 $\mu\text{g}/\text{m}^3$), and lower than that in India (10–30 $\mu\text{g}/\text{m}^3$) during the COVID-19 epidemic (Sharma et al., 2020; Singh & Chauhan, 2020; Tobias et al., 2020). CO exhibited similar spatial variation to $\text{PM}_{2.5}$ during the periods I and II, with a higher concentration in the northern YRD and lower concentration in the southern YRD.

Unlike NO_2 , O_3 in the YRD shows no significant difference in spatial distribution during periods I, II, and III. O_3 in the northern YRD seems higher than that in the southern YRD during the period IV. According to media reports (https://www.sohu.com/a/370746933_440288), Wenzhou, the southernmost city in the YRD, became the second worst-hit area next to Hubei Province, of which the capital city is Wuhan. Thus, NO_2 concentration in Wenzhou was very low (7 $\mu\text{g}/\text{m}^3$) during the period II due to the most rigorous control measures, whereas O_3 concentration (70 $\mu\text{g}/\text{m}^3$) in Wenzhou during the period II was at a higher level (Fig. 4). A similar O_3 increase was reported in Milan, Italy, during the lockdown (Collivignarelli et al., 2020). The elevated O_3 concentration during the lockdown was probably due to less NO emission and the weakened NO titration effect (Tan et al., 2009).

Period I represents a normal period, and period II represents the most rigorous control period due to the novel coronavirus. Percent changes (a positive value means an increase and a negative value means decrease) of the air pollutants in the YRD during period II when compared to the period I are mapped in Fig. 5. NO_2 in the most YRD cities decreased by more than 50% (average 58.2%) during the period II and NO_2 in the southern YRD even reduced up to 70–80%. $\text{PM}_{2.5}$ and PM_{10} in the most YRD cities decreased by 30–40% during period II, with the average proportion of 37% and 35%, respectively. Averagely, the proportion of O_3 increase in the YRD was 81% during period II and that was 101–155% in the provincial capital cities.

Fig. 4 Spatial variation of NO_2 , $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO , and O_3 in the YRD during the four periods. The provincial capital cities and Shanghai were labeled

Fig. 5 Percent changes of the air pollutants in the YRD during period II when compared to the period I. A negative value indicates decrease and a positive value indicates an increase

Analysis of meteorological conditions

Time series of daily average of precipitation, total column water vapor, and wind speed in the YRD region during the study period in 2020 are in Fig. S1. It seems that precipitation was evenly distributed and wind speed was similar during the study period in 2020. Total column water vapor shows an increasing trend from January to May, 2020. Independent-sample *T* test was applied to exam the significant difference of meteorological parameters during the four periods. There was no significant difference ($P \gg 0.05$) in precipitation between the four periods, as well as wind speed. Significant differences were obtained for the total column water vapor in the four periods, verifying

an increasing trend of total column water vapor. The speed and direction of the horizontal wind at a height of 10 m above the ground surface in the YRD region during the four periods in 2020 are depicted in Fig. 6. Wind fields during period I and period II were similar, with the prevailing wind from the north and northeast. Compared to period I and period II, the predominant wind direction changed in period III and period IV, with the prevailing wind from the east, southeast, and south.

Comparison with 2019

For comparison, average concentrations of pollutants in the four periods in 2020 with that in 2019 are listed in Table 1. Time series of hourly concentrations of

Fig. 6 The speed and direction of the horizontal wind at a height of 10 m above the ground surface in the YRD region during the four periods in 2020

pollutants during the four periods in 2020 and 2019 are depicted in Fig. S2. From Table 1, concentrations of pollutants, except O_3 , generally decreased during the four periods in 2020 when compared to 2019. However, a larger reduction of pollutants was

observed during period II, which was closely related to the strict lockdown policy in period II. For example, NO_2 during the numbered four periods in 2020 decreased by 18.2%, 45.1%, 24.8%, and 3.9%, respectively, when compared to that in 2019. Similarly,

Table 1 Comparison of average concentrations of pollutants during the four periods in 2020 and 2019

Pollutants	Year	Period I	Period II	Period III	Period IV
PM _{2.5} (µg/m ³)	2020	65	41	35	33
	2019	74	59	53	34
	Percent change (%) [*]	−12.3	−30.2	−33.2	−3.6
PM ₁₀ (µg/m ³)	2020	79	51	59	61
	2019	102	78	84	63
	Percent change (%)	−22.9	−35.1	−29.0	−2.8
NO ₂ (µg/m ³)	2020	39	16	29	29
	2019	47	30	39	30
	Percent change (%)	−18.2	−45.1	−24.8	−3.9
SO ₂ (µg/m ³)	2020	8	7	7	8
	2019	11	8	10	9
	Percent change (%)	−28.7	−17.7	−28.4	−9.5
O ₃ (µg/m ³)	2020	36	64	64	93
	2019	30	49	67	83
	Percent change (%)	20.3	32.3	−3.8	12.5
CO (mg/m ³)	2020	0.952	0.682	0.633	0.625
	2019	1.033	0.850	0.754	0.638
	Percent change (%)	−7.8	−19.8	−16.0	−2.1

^{*}Percent changes of the air pollutants in the YRD during the four periods in 2020 when compared to 2019. A negative value indicates decrease and a positive value indicates an increase

PM₁₀ during the four periods in 2020 decreased by 22.9%, 35.1%, 29%, and 2.8%, respectively. In contrast to other pollutants, O₃, a typical secondary pollutant formed from photochemical reaction, presented an increasing trend during the study period in 2020, compared to 2019. Further, a larger increase in O₃ was observed in period II in 2020 (32.3%), which provided evidence that O₃ increased due to reduction of NO_x emission during period II. SO₂ in period II in 2020 was similar to that in 2019. In period IV, concentrations of pollutants in 2020, except O₃, were similar to that in 2019, which was directly associated with the intensive resumption of work and production on national scale.

Figure 7 shows percentage changes in the concentrations of pollutants, electricity consumption, and highway transportation in YRD in 2020 when compared to the corresponding monthly average in 2019. The monthly average concentrations of air pollutants in YRD were downloaded from Yangtze River Delta regional air quality forecast business platform. Compared to 2019, the six pollutants indicating air quality in the YRD decreased in 2020 except O₃. For temporal comparison, a larger reduction of pollutants in the YRD was observed in the first three months of 2020, especially in February. For example, NO₂, PM_{2.5}, PM₁₀, SO₂, and CO decreased by 37%, 38%, 34%,

19%, and 26% in February, 2020, respectively. Similar results were reported in Wuhan in central China, which was attributed to emission reduction (92.0%) rather than meteorological conditions during the lockdown (Zheng et al., 2020). O₃ (8-h maximum) in the YRD presented an increasing trend in 2020 when compared to 2019. O₃ (8-h maximum) increased by 14%, 17%, and 18% in January, February, and April, respectively.

Seventy-three percent of the total freight transport in China was achieved by highway transportation in 2019. Compared to 2019, reduction (1.4–35.2%) of highway freight transportation in the YRD was recorded from January to May in 2020, particularly in February (Fig. 7b). For example, highway freight transportation in Shanghai, Jiangsu, Zhejiang, and Anhui decreased by 27.2%, 35.2%, 21.4%, and 19.2% in February 2020, respectively, and started to resume since March. Compared to highway freight transportation, a larger reduction of highway passenger transportation was recorded in 2020 than that in 2019. No significant resumption of highway passenger transportation was observed in the YRD from March in 2020. For example, highway passenger transportation reduced by 50.6–60.3% in February, and that was 37.9–70.8% in May 2020, compared to the same period in 2019.

Fig. 7 Percentage changes in **a** the concentrations of pollutants, **b** highway transportation, and **c** electricity consumption in the YRD in 2020 when compared to the corresponding monthly average in 2019. The monthly electricity consumption

structure in Jiangsu and Shanghai during the study period was not available. Source: (Ministry of Transport of the People's Republic of China, 2020; Statistics Bureau of Anhui Province, 2020; Statistics Bureau of Zhejiang Province, 2020)

Total electricity consumption is closely related to industrial production because electricity consumption from industry accounts for a dominant proportion. The electricity consumption from industry accounted for 69% of the total electricity consumption in China, with service, residential, and agriculture proportion of 16%, 14%, and 1%, respectively (National Energy Administration, 2020). From Fig. 7c, compared to 2019, the total electricity consumption of Zhejiang and Anhui reduced in February in 2020, which was resulted from large reduction of electricity consumption from industry. For example, industrial electricity consumption of Zhejiang and Anhui reduced by 32.4% and 50.6%, respectively, which was related to the

lockdown policy. The total electricity consumption in the YRD during the study period in 2020 slightly reduced when compared to that in 2019.

In summary, the air quality in the YRD region greatly improved during the study period in 2020 due to the countermeasures to interrupt the transmission of COVID-19 when compared with the same period in 2019. However, increasing O_3 is worthy of attention.

Conclusion

This lockdown in China due to the novel coronavirus outbreak provided a unique chance to test the

sensitivity of primary emission reduction on air quality. Our results show that NO₂ significantly decreased and SO₂ almost remain unchanged in the YRD region during the period of the COVID-19 outbreak when the most rigorous control measures were implemented. Under the circumstances, PM_{2.5} in the northern YRD areas still exhibited higher concentrations when compared to the case in which NO₂ increased, implying enhanced secondary formation. The results demonstrated that PM_{2.5} shows a nonlinear response to the reduction of its precursors and this phenomenon varies from region to region. O₃ increase was also recorded during the COVID-19 outbreak, which was probably related to the weakened NO titration effect. Further researches need to probe into the nonlinear response mechanism and regulation principle of PM_{2.5}, O₃, and their precursors.

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Author contribution Lan Yao: conceptualization, data curation, writing—original draft, supervision, funding acquisition, and project administration. Weiye Li: data curation, writing—review & editing, and funding acquisition. Yi Du: data curation and formal analysis. All authors read and approved the final manuscript.

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Data Availability The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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