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Significant concurrent decrease in PM$_{2.5}$ and NO$_2$ concentrations in China during COVID-19 epidemic

Biwu Chu$^{1,2,3}$, Shuping Zhang$^{1,3}$, Jun Liu$^{1,3}$, Qingxin Ma$^{1,2,3}$, Hong He$^{1,2,3,*}$

$^1$ State Key Joint Laboratory of Environment Simulation and Pollution Control, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
$^2$ Center for Excellence in Regional Atmospheric Environment, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
$^3$ University of Chinese Academy of Sciences, Beijing 100049, China

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**ABSTRACT**

The strict control measures and social lockdowns initiated to combat COVID-19 epidemic have had a notable impact on air pollutant concentrations. According to observation data obtained from the China National Environmental Monitoring Center, compared to levels in 2019, the average concentration of NO$_2$ in early 2020 during COVID-19 epidemic has decreased by 53%, 50%, and 30% in Wuhan city, Hubei Province (Wuhan excluded), and China (Hubei excluded), respectively. Simultaneously, PM$_{2.5}$ concentration has decreased by 35%, 29%, and 19% in Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded), respectively. Less significant declines have also been found for SO$_2$ and CO concentrations. We also analyzed the temporal variation and spatial distribution of air pollutant concentrations in China during COVID-19 epidemic. The decreases in PM$_{2.5}$ and NO$_2$ concentrations showed relatively consistent temporal variation and spatial distribution. These results support control of NO$_2$ to further reduce PM$_{2.5}$ pollution in China. The concurrent decrease in NO$_x$ and PM$_{2.5}$ concentrations resulted in an increase of O$_3$ concentrations across China during COVID-19 epidemic, indicating that coordinated control of other pollutants is needed.

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**Introduction**

Coronavirus disease 2019 (COVID-19) has spread rapidly all over the world. As of 12 May 2020, the total accumulative cases of COVID-19 epidemic exceeded four million. In China, this novel pneumonia-like disease of unknown origin was first reported in December 2019 in Wuhan city, Hubei Province. Soon afterwards, due to dramatical increase of COVID-19 case numbers, the government officially closed urban transportation system in Wuhan on 23 January 2020. Subsequently, all 31 provincial regions in Chinese mainland, including Hubei (with its capital city Wuhan), began initiating their first-level response to a major public health emergency. By 25 January 2020, which was the start of the Chinese spring festival (i.e., Chinese New Year, CNY), an increasing number of control measures were introduced by local governments to reduce gatherings and travel. The strictest control measures lasted until 23 February 2020, after the peak in COVID-19 case numbers in China. Then, based on the sustained downward trend in COVID-19 case numbers, the Chinese government allowed the resumption of livelihoods and industries by stages and
districts. In late March of 2020, the transmission of COVID-19 experienced a substantial decline in China, while cases imported from foreign countries became the dominate source. By 2 May 2020, the 31 provincial regions in Chinese mainland, including Hubei, terminated their public health emergency first-level response.

The measures and lockdowns introduced to stop the spread of COVID-19 in China have had a remarkable impact on industrial production and social life, and therefore have likely had an effect on pollutant emissions and environmental air quality. Unlike stringent emission controls, the declines in pollutant emissions during COVID-19 epidemic have primarily come from changes in social life and light industry, with power generators and heavy industry expected to be less affected. Stringent emission controls have been shown to be effective for temporary improvement of air quality during specific events, such as the 2008 Beijing Olympic Games (Wang et al., 2010; Xing et al., 2011) and 2014 Asia-Pacific Economy Cooperation (APEC) China Summit (Sun et al., 2016; Xu et al., 2019). The COVID-19 epidemic has provided the opportunity to investigate the influence of changes in societal production and life on air quality. In this study, based on analysis of concentrations of nitrogen dioxide (NO$_2$), sulfur dioxide (SO$_2$), carbon monoxide (CO), ozone (O$_3$), particulate matter with an aerodynamic diameter less than 2.5 $\mu$m (PM$_{2.5}$), and particulate matter with an aerodynamic diameter less than 10 $\mu$m (PM$_{10}$) obtained from the China National Environmental Monitoring Center (CNEMC), we evaluated changes in air quality in Wuhan, Hubei, and China. This study could have considerable implications for air pollution control in China and possibly elsewhere.

1. Materials and methods

1.1. Monitoring network

Established by the Ministry of Ecology and Environment of China (MEE), the CNEMC network (http://106.37.208.233:20035) began measuring surface PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, O$_3$, and CO concentrations in China in 2013. Both PM$_{2.5}$ and PM$_{10}$ mass concentrations are measured using oscillating microbalance and/or $\beta$ absorption; SO$_2$ concentrations are measured by ultraviolet (UV) fluorescence; CO and O$_3$ concentrations are measured using infrared and UV absorption, respectively; and, NO$_2$ concentrations are measured by a molybdenum converter and chemiluminescence. Details of the specifications and procedures of the measurements are listed on the MEE website: http://kjs.mee.gov.cn/hjbhbz/bzwb/jcfbz/201308/t20130802_256852.shtml (2019/08/18), and http://kjs.mee.gov.cn/hjbhbz/bzwb/jcfbz/201308/t20130802_256853.shtml (2019/08/18). The network now includes 1656 sites in 378 cities. In the current study, hourly data from 365 cities with measurements from 2015 to early 2020 were used.

1.2. Data quality control

Similar data quality control methods as employed in previous studies (Shi et al., 2018; Wu et al., 2018) were used to reduce errors in the CNEMC monitoring network dataset. First, zero or negative concentrations were set as missing. Second, extreme outlier concentrations were deleted (i.e., SO$_2$ > 1428 $\mu$g/m$^3$, NO$_2$ > 1026 $\mu$g/m$^3$, CO > 62.5 mg/m$^3$, PM$_{2.5}$ > 10 000 $\mu$g/m$^3$, PM$_{10}$ > 10 000 $\mu$g/m$^3$, O$_3$ > 1071 $\mu$g/m$^3$). Third, identical data repeated three or more times, which were likely duplicated by the monitoring network reporting system due to communication error (Rohde and Muller, 2015), were also set as missing, except for the first value. Fourth, temporally inconsistent outliers were removed following Wu et al. (2018).

2. Results and discussion

2.1. Changes in air pollutant concentrations

Our results indicated a concurrent significant change in air pollutant concentrations in China with the introduction of control measures and societal lockdowns to limit COVID-19 spread. Based on the increase in COVID-19 cases and corresponding control measures in China, we first selected the period from 21 January to 23 March as a whole to analyze changes in pollutant concentrations in early 2020 with COVID-19 epidemic. Although CNY could have a significant influence on air quality (Zhang et al., 2016), this event was included within the study time-frame in both 2019 and 2020. Compared with the same period in 2019, the COVID-19 epidemic control measures in early 2020 coincided with significant reductions in NO$_2$ concentrations in Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded) (by 53%, 50%, and 30%, respectively; Fig. 1). These reductions are comparable with the decrease of NO$_2$ column concentrations observed with satellites (Bauwens et al., 2020). An important reason for the decrease in NO$_2$ should be the significant reductions (40%-80%) of city traffic in eastern and northern China during COVID-19 epidemic (Wang et al., 2020). Coinciding with the decrease in

![Fig. 1 – Air pollutant concentrations during spread of COVID-19 in Wuhan, Hubei Province (Wuhan excluded), and China (Hubei excluded) in early 2020 and the changes (%) during COVID-19 epidemic compared to corresponding periods (21 January to 23 March) in 2019.](image-url)
NO\textsubscript{2}, PM\textsubscript{2.5} concentrations also showed an obvious decrease compared to levels in 2019, with reductions of 35%, 29%, and 19% in Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded), respectively. The PM\textsubscript{10} concentrations also decreased, with similar percentage reductions as that of PM\textsubscript{2.5}. This might indicate that the secondary aerosol and primary aerosol decreased with similar percentages during COVID-19 epidemic since higher percentage of primary aerosol contributed to PM\textsubscript{10} than that to PM\textsubscript{2.5} (Seinfeld and Pandis, 2006). The percentage changes in NO\textsubscript{2} and PM\textsubscript{2.5} concentrations were similar in background area with those in urban area. Compared to levels in 2019, the concentrations of SO\textsubscript{2} and CO also decreased during COVID-19 epidemic in 2020, but at much lower rates than that observed for NO\textsubscript{2}, PM\textsubscript{2.5} and PM\textsubscript{10}. The decreases in SO\textsubscript{2} and CO were not significant in background area of Wuhan or Hubei (Table S1). In general, NO\textsubscript{2} and PM\textsubscript{2.5} showed marked decreases and SO\textsubscript{2} and CO exhibited much smaller decreases. These phenomena indicated that the emission from stationary sources, such as coal-fired power plants, iron and steel production, didn’t decreased as much as traffic. In contrast, due to less NO to react with O\textsubscript{3} (Seinfeld and Pandis, 2006), as well as less heterogeneous HO\textsubscript{2} radical loss and higher actinic flux with lower concentration of particle (Li et al., 2019b), O\textsubscript{3} demonstrated a notable increase, with a higher rate observed in Wuhan (58%) than Hubei or China.

2.2. Spatial distribution of air pollutant concentrations

Fig. 2 shows the spatial distribution of air pollutant concentrations from 21 January to 23 March in both 2019 and 2020 as well as the percentage changes. The decreases in NO\textsubscript{2} and PM\textsubscript{2.5} showed similar spatial distributions. The most significant decreases in NO\textsubscript{2} and PM\textsubscript{2.5} occurred in the North China Plain and Yangtze River Delta, covering most of east-central China. SO\textsubscript{2} also showed a decreasing trend, with the most obvious decrease observed in the North China Plain. Changes in CO concentrations were not significant enough to show obvious distribution characteristics. In contrast, O\textsubscript{3} concentrations increased across most of China, with the most significant increase observed in the Yangtze River Delta, especially Hubei Province.

2.3. Temporal variation in pollutant concentrations

To further analyze the influence of COVID-19 epidemic control measures and lockdowns on air quality, temporal variations in pollutant concentrations in different stages of COVID-19 spread were analyzed. Five periods, i.e. P1 to P5, were selected as different stages of COVID-19 outbreak in early 2020. P1 (7 December 2019 to 20 January 2020) was the early stage before the outbreak of COVID-19 epidemic in China. In P2 (21 January to 6 February), COVID-19 case numbers dramatically increased, coincided with an increasing number of control measures. The government officially closed Wuhan before CNY and all 31 provincial regions in Chinese mainland began initiating their first-level response to a major public health emergency in this stage. In P3 (7 February to 22 February), the peak in COVID-19 case numbers appeared in China, coincided with strictest control measures in this stage. In P4 (23 February to 23 March), livelihoods and industries began to resume by stages and districts with the sustained downward trend in COVID-19 epidemic case numbers. In P5 (24 March to 22 April), the livelihoods and industries were basically restored to order and the first-level responses to public health emergency were terminated. As COVID-19 spread coincided with the CNY, we compared the temporal variations of pollutant concentrations in similar time periods relative to CNY from 2015 to 2019 (see more details in Table S2).

As shown in Fig. 3 and Figs. S1–S3, the concentrations of air pollutants in P1 were similar in 2015 to 2020. The concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} showed a decrease a few days before CNY in P2 due to the national holiday. In 2015 to 2019, the concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} returned to normal after two weeks when the holiday period ended in P3. In 2020, however, coinciding with the spread of COVID-19 and its targeted control measures, NO\textsubscript{2} and PM\textsubscript{2.5} levels remained low in P3 and P4. The trend of NO\textsubscript{2} concentrations in Fig. 3 is consistent with the tropospheric NO\textsubscript{2} column observations from the satellite (Zhang et al., 2020). After people resumed work in stages and by districts during P4, the concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} returned to normal levels in P5. According to the temporal variation of pollutant concentrations, concentrations of NO\textsubscript{2} and PM\textsubscript{2.5} decreased most significantly in P3, although concentrations were also affected by the measures and lockdowns in P2 and P4, which were consistent with the strict degrees of control measures in different periods.

The declines in concentrations differed for different air pollutants, as shown in Fig. 4 and Tables S3–S5. NO\textsubscript{2} concentrations showed the most significant decrease. In P3 when the strictest control measures were introduced, compared to levels in 2019, NO\textsubscript{2} concentrations in 2020 decreased by 57%, 61%, and 51% in Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded), respectively. Coinciding with the decline in NO\textsubscript{2} levels, PM\textsubscript{2.5} concentrations in P3 also showed an obvious decrease in 2020 compared to 2019, with 51%, 47%, and 39% reductions in Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded), respectively. The decrease of concentrations of SO\textsubscript{2} and CO was not significant in 2020 compared to 2019 in Wuhan or Hubei (Tables S3–S5), even in P3, which may indicate that coal burning did not vary much under COVID-19 epidemic control measures.

As shown in Tables S3–S5, O\textsubscript{3} levels primarily increased in P2. During this period, O\textsubscript{3} concentrations increased by 40%–60% in Wuhan and Hubei in 2020 compared to levels in 2019. However, with continuous decrease in NO\textsubscript{2} concentrations, O\textsubscript{3} concentrations did not further increase in P3. In background areas in Wuhan and other cities in Hubei, NO\textsubscript{2} concentrations decreased by about 70% and PM\textsubscript{2.5} decreased by about 60% in P3 in 2020 compared to levels in 2019, whereas the O\textsubscript{3} concentration only increased by 2%–4% (Tables S3–S4). These results indicate that a significant reduction in NO\textsubscript{x} may overcome the increase in O\textsubscript{3} concentration due to the concurrent decrease in both NO\textsubscript{x} and PM\textsubscript{2.5}, thereby progressing toward the coordinated control of both PM\textsubscript{2.5} and O\textsubscript{3}.

3. Summary and implications

The changes in air pollutant concentrations due to the introduction of COVID-19 epidemic control measures indicated
Fig. 2 – Spatial distribution of air pollutant concentrations from 21 January to 23 March in 2019 and 2020, and changes in percentage of concentrations.
that the resulting changes in societal production and life had a notable impact on pollutant emissions and air quality. Following social lockdown, traffic intensity decreased markedly (Wang et al., 2020), leading to a significant decrease in NO\textsubscript{2} concentrations, given that power generators and heavy industry were less affected. NO\textsubscript{2} plays key roles in the formation of atmospheric secondary aerosol (Cheng et al., 2016; Chu et al., 2019; He et al., 2014; Russell et al., 1988), which is the main contributor of PM\textsubscript{2.5} mass in China (Chen et al., 2020; Fu et al., 2016; Huang et al., 2014; Liu et al., 2015). Due to the more rapid decrease in SO\textsubscript{2} emissions than NO\textsubscript{2} in recent years, aerosol pollution has shifted from sulfate-dominated to nitrate-dominated in many eastern Chinese cities (Li et al., 2019a; Wen et al., 2018). NO\textsubscript{2} is also highly active in the formation of oxidants in the gas phase, such as O\textsubscript{3} and OH and NO\textsubscript{3} radicals (Seinfeld and Pandis, 2006), and contributes to oxidation capacity in heterogeneous and aqueous reactions (Chen et al., 2019; Cheng et al., 2016; He et al., 2014; Xue et al., 2016). The results of this study corroborated the above mechanisms. The relatively consistent temporal variation and spa-

Fig. 3 – Temporal variations in NO\textsubscript{2} and PM\textsubscript{2.5} concentrations during COVID-19 epidemic in urban areas of Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded) in early 2020 and corresponding periods in 2015 to 2019. Day 0 indicates Chinese New Year (CNY) each year. P1 to P4 are the early stage before the outbreak, the rapid growth period, the fastigium, and the decline period of COVID-19 epidemic, respectively. P5 is the period when the livelihoods and industries were basically restored to order. Detail information of P1 to P5 in each year is listed in Table S2.
Fig. 4 – NO$_2$ and PM$_{2.5}$ concentrations in different periods during COVID-19 epidemic in urban areas of Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded) in early 2020 and corresponding periods relative to CNY in 2015 to 2019. Error bar is one standard variation of day-average concentrations in each period. Period 1 to 5 are the same as P1 to P5 in Fig. 3. Period 1 to 4 are the early stage before the outbreak, the rapid growth period, the fastigium, and the decline period of COVID-19 epidemic, respectively. Period 5 is the period when the livelihoods and industries were basically restored to order. Detail information of period 1 to 5 in each year is listed in Table S2.

The decrease in NO$_x$ and PM$_{2.5}$ concentrations may cause an increase in O$_3$ concentration, in coal-fired power plants in China (Zheng et al., 2018). VOCs and NH$_3$ are derived from a wealth of sources, with a lack of effective control methods relative to NO$_x$ (Fu et al., 2017; Liu et al., 2015; Zheng et al., 2018). These situations, plus the finding of coincidental decreases in PM$_{2.5}$ and NO$_x$ concentrations in this study, support the control of NO$_x$ to further reduce PM$_{2.5}$ pollution in China. The decrease in NO$_x$ and PM$_{2.5}$ concentrations may cause an increase in O$_3$ concentration, in-
indicating the need for coordinated control of VOCs. However, in some areas where control of VOCs is difficult, a high reduction in NOₓ may overcome the increase of O₃ concentration due to the decrease in both NOₓ and PM₂.₅, thus progressing toward coordinated control of PM₂.₅ and O₃.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2020.06.031.

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