Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jes

JES JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

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*

ARTICLE INFO

Article history:
Received 30 May 2020
Revised 23 June 2020
Accepted 23 June 2020
Available online 1 July 2020

Keywords:
Covid-19 epidemic
Air quality
Temporal variation and spatial distribution
Coordinated control
$PM_{2.5}$
O_3

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_x 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.

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

* Corresponding author.
E-mail address: honghe@rcees.ac.cn (H. He).

https://doi.org/10.1016/j.jes.2020.06.031
1001-0742/

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 μm ($PM_{2.5}$), and particulate matter with an aerodynamic diameter less than 10 μm (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 β 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/jcffbz/201308/t20130802_256852.shtml (2019/08/18), and http://kjs.mee.gov.cn/hjbhbz/bzwb/jcffbz/201308/t20130802_256853.shtml (2019/08/18). The network now includes 1 656 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 μg/m^3, NO_2 > 1026 μg/m^3, CO > 62.5 mg/m^3, $PM_{2.5}$ > 10000 μg/m^3, PM_{10} > 10000 μg /m^3, O_3 > 1071 μg/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).

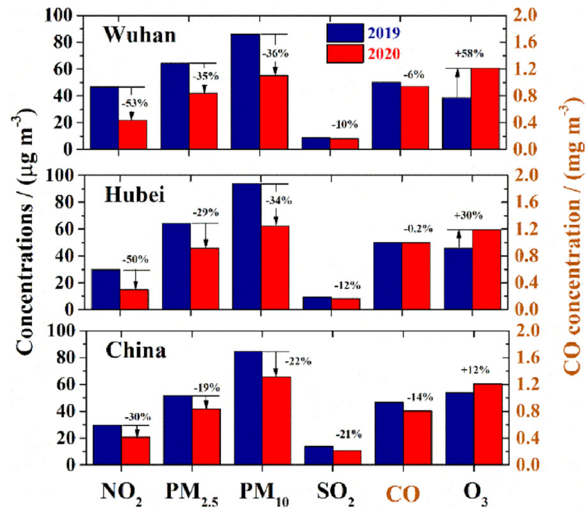

Fig. 1 – Air pollutant concentrations during spread of COVID-19 in Wuhan, Hubei Province (Wuhan excluded), and China (Hubei excluded) in early 2020 and the changes (%) during COVID-19 epidemic compared to corresponding periods (21 January to 23 March) in 2019.

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., 2010), 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 of 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

NO_2, $PM_{2.5}$ 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_{10} concentrations also decreased, with similar percentage reductions as that of $PM_{2.5}$. 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_{10} than that to $PM_{2.5}$ (Seinfeld and Pandis, 2006). The percentage changes in NO_2 and $PM_{2.5}$ concentrations were similar in background area with those in urban area. Compared to levels in 2019, the concentrations of SO_2 and CO also decreased during COVID-19 epidemic in 2020, but at much lower rates than that observed for NO_2, $PM_{2.5}$ and PM_{10}. The decreases in SO_2 and CO were not significant in background area of Wuhan or Hubei (Table S1). In general, NO_2 and $PM_{2.5}$ showed marked decreases and SO_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_3 (Seinfeld and Pandis, 2006), as well as less heterogeneous HO_2 radical loss and higher actinic flux with lower concentration of particle (Li et al., 2019b), O_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_2 and $PM_{2.5}$ showed similar spatial distributions. The most significant decreases in NO_2 and $PM_{2.5}$ occurred in the North China Plain and Yangtze River Delta, covering most of east-central China. SO_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_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_2 and $PM_{2.5}$ showed a decrease a few days before CNY in P2 due to the national holiday. In 2015 to 2019, the concentrations of NO_2 and $PM_{2.5}$ 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_2 and $PM_{2.5}$ levels remained low in P3 and P4. The trend of NO_2 concentrations in Fig. 3 is consistent with the tropospheric NO_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_2 and $PM_{2.5}$ returned to normal levels in P5. According to the temporal variation of pollutant concentrations, concentrations of NO_2 and $PM_{2.5}$ 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_2 concentrations showed the most significant decrease. In P3 when the strictest control measures were introduced, compared to levels in 2019, NO_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_2 levels, $PM_{2.5}$ 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_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_3 levels primarily increased in P2. During this period, O_3 concentrations increased by 40%–60% in Wuhan and Hubei in 2020 compared to levels in 2019. However, with continuous decrease in NO_2 concentrations, O_3 concentrations did not further increase in P3. In background areas in Wuhan and other cities in Hubei, NO_2 concentrations decreased by about 70% and $PM_{2.5}$ decreased by about 60% in P3 in 2020 compared to levels in 2019, whereas the O_3 concentration only increased by 2%–4% (Tables S3–S4). These results indicate that a significant reduction in NO_x may overcome the increase in O_3 concentration due to the concurrent decrease in both NO_x and $PM_{2.5}$, thereby progressing toward the coordinated control of both $PM_{2.5}$ and O_3.

3. Summary and implications

The changes in air pollutant concentrations due to the introduction of COVID-19 epidemic control measures indicated

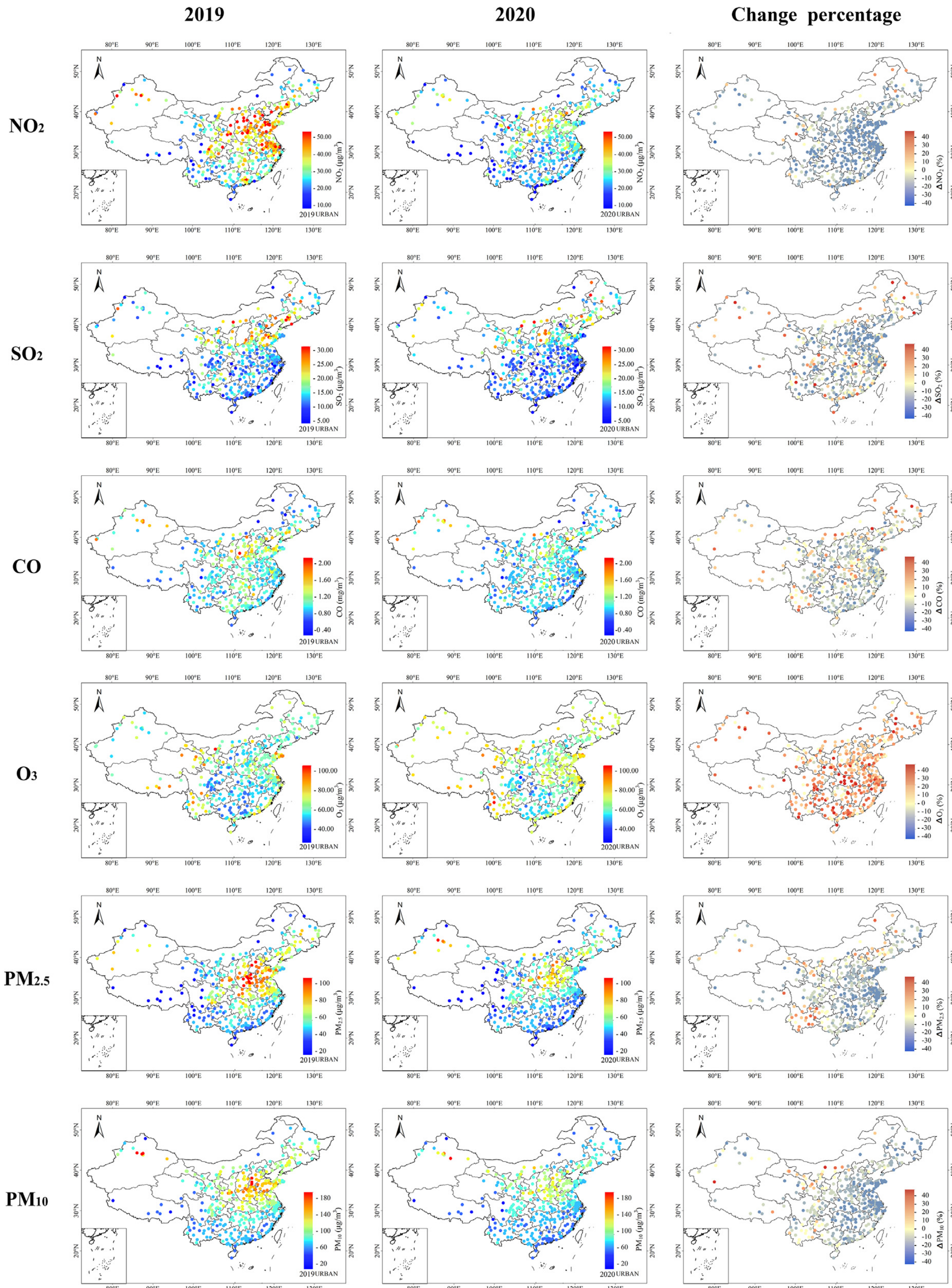

Fig. 2 – Spatial distribution of air pollutant concentrations from 21 January to 23 March in 2019 and 2020, and changes in percentage of concentrations.

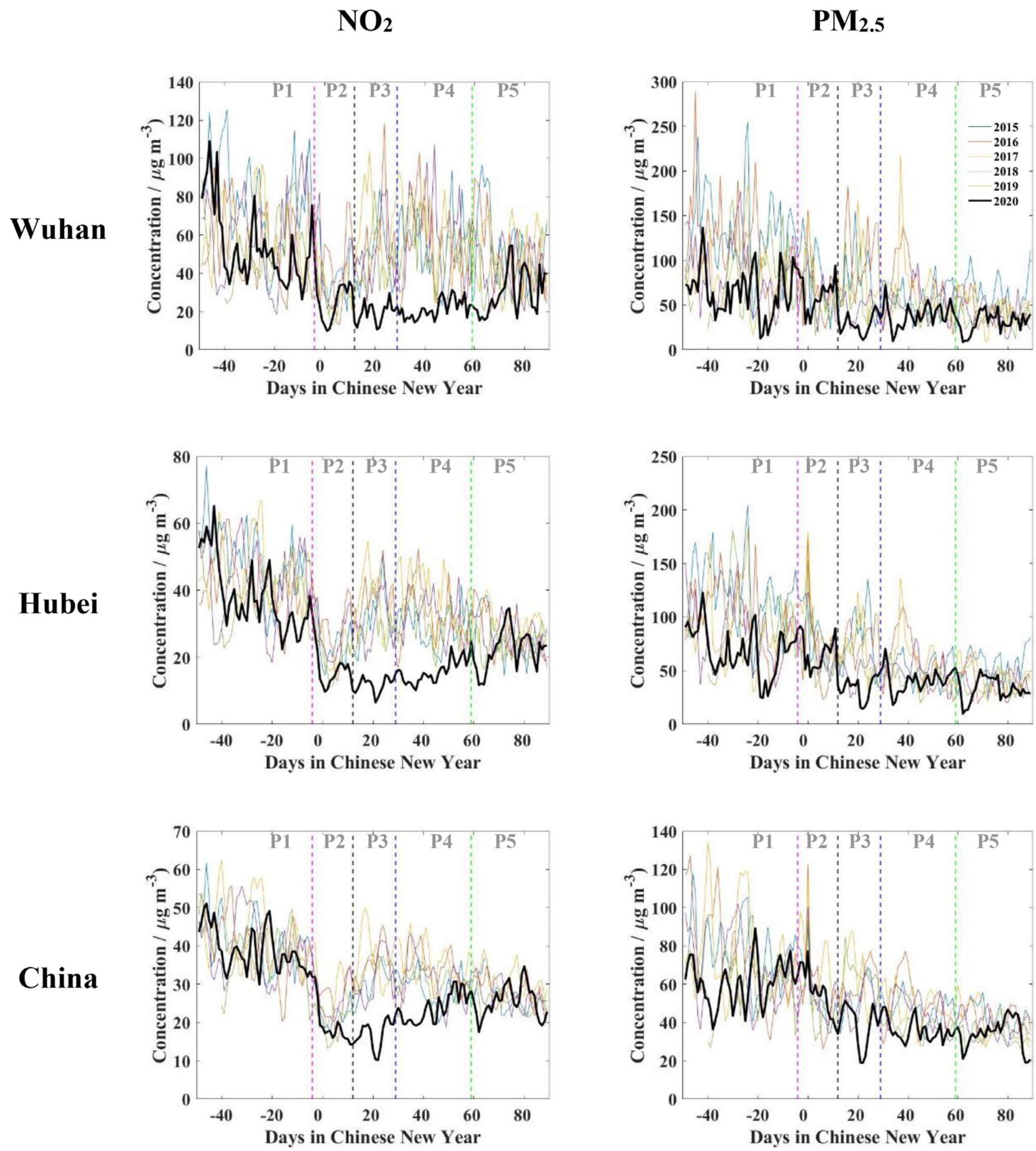

Fig. 3 – Temporal variations in NO_2 and $PM_{2.5}$ concentrations during COVID-19 epidemic in urban areas of Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded) in early 2020 and corresponding periods in 2015 to 2019. Day 0 indicates Chinese New Year (CNY) each year. P1 to P4 are the early stage 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.

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_2 concentrations, given that power generators and heavy industry were less affected. NO_x 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 $PM_{2.5}$ 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_2 emissions than NO_x 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_x is also highly active in the formation of oxidants in the gas phase, such as O_3 and OH and NO_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-

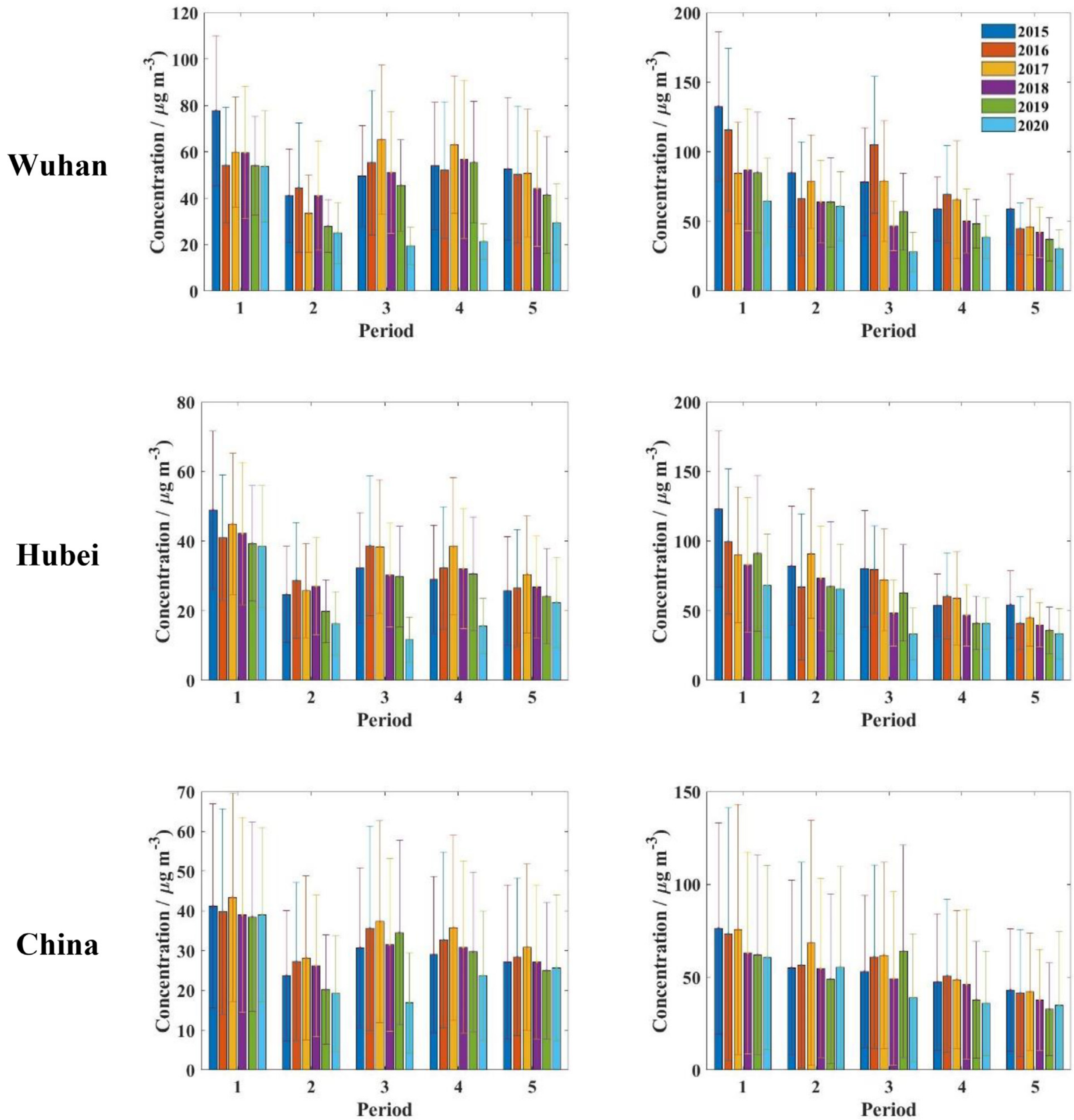

Fig. 4 – NO_2 and $PM_{2.5}$ concentrations in different periods during COVID-19 epidemic in urban areas of Wuhan, Hubei (Wuhan excluded), and China (Hubei excluded) in early 2020 and corresponding periods relative to CNY in 2015 to 2019. Error bar is one standard variation of day-average concentrations 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.

tial distributions of changes in concentration of $PM_{2.5}$ and NO_2 following the introduction of strict COVID-19 epidemic control measures indicated that $PM_{2.5}$ is highly related to NO_2.

SO_2, NO_x, NH_3, and volatile organic compounds (VOCs) are the key precursors of secondary $PM_{2.5}$ (Ding et al., 2016; Kerminen, 1999; Liu et al., 2013; Meng et al., 2011). At present, the economic costs for further substantial decreases in SO_2 emissions will be huge after the universal desulphurization 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_2 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, indicating the need for coordinated control of VOCs. However, in some areas where control of VOCs is difficult, a high reduction in NO_x may overcome the increase of O_3 concentration due to the decrease in both NO_x and $PM_{2.5}$, thus progressing toward coordinated control of $PM_{2.5}$ and O_3.

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.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 41877304), the National Key R&D Program of China (No. 2018YFC0506901), and the Youth Innovation Promotion Association, CAS (Nos. 2018060 and 2018055). The authors would like to thank Prof. Jingkun Jiang and Dr. Wei Zhou for their help collecting monitoring data from the CNEMC network, and thank Ms. Ting Chu for her help editing the figures.

Supplementary materials

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

REFERENCES

Bauwens, M., Compernolle, S., Stavrakou, T., Müller, J.-F., van Gent, J., Eskes, H., et al., 2020. Impact of coronavirus outbreak on NO_2 pollution assessed using TROPOMI and OMI observations. Geophys. Res. Lett. e2020GL087978.

Chen, T., Chu, B., Ge, Y., Zhang, S., Ma, Q., He, H., et al., 2019. Enhancement of aqueous sulfate formation by the coexistence of NO_2/NH_3 under high ionic strengths in aerosol water. Environ. Pollut. 252, 236–244.

Chen, T., Liu, J., Liu, Y., Ma, Q., Ge, Y., Zhong, C., et al., 2020. Chemical characterization of submicron aerosol in summertime Beijing: a case study in southern suburbs in 2018. Chemosphere 247, 125918.

Cheng, Y., Zheng, G., Wei, C., Mu, Q., Zheng, B., Wang, Z., et al., 2016. Reactive nitrogen chemistry in aerosol water as a source of sulfate during haze events in China. Sci. Adv. 2, e1601530.

Chu, B., Wang, Y., Yang, W., Ma, J., Ma, Q., Zhang, P., et al., 2019. Effects of NO_2 and C_3H_6 on the heterogeneous oxidation of SO_2 on TiO_2 in the presence or absence of UV–Vis irradiation. Atmos. Chem. Phys. 19, 14777–14790.

Ding, X., He, Q.F., Shen, R.Q., Yu, Q.Q., Zhang, Y.Q., Xin, J.Y., et al., 2016. Spatial and seasonal variations of isoprene secondary organic aerosol in China: significant impact of biomass burning during winter. Sci. Rep. 6, 20411.

Fu, X., Wang, S.X., Xing, J., Zhang, X.Y., Wang, T., Hao, J.M., 2017. Increasing ammonia concentrations reduce the effectiveness of particle pollution control achieved via SO_2 and NO_X emissions reduction in east China. Environ. Sci. & Technol. Lett. 4, 221–227.

Fu, X.X., Wang, X.M., Hu, Q.H., Li, G.H., Ding, X., Zhang, Y.L., et al., 2016. Changes in visibility with $PM_{2.5}$ composition and relative humidity at a background site in the pearl river delta region. J. Environ. Sci. 40, 10–19.

He, H., Wang, Y., Ma, Q., Ma, J., Chu, B., Ji, D., et al., 2014. Mineral dust and NO_x promote the conversion of SO_2 to sulfate in heavy pollution days. Sci. Rep. 4, 04172.

Huang, R.-J., Zhang, Y., Bozzetti, C., Ho, K.-F., Cao, J.-J., Han, Y., et al., 2014. High secondary aerosol contribution to particulate pollution during haze events in China. Nature 514, 218–222.

Kerminen, V.M., 1999. Roles of SO_2 and secondary organics in the growth of nanometer particles in the lower atmosphere. J. Aerosol Sci. 30, 1069–1078.

Li, H.Y., Cheng, J., Zhang, Q., Zheng, B., Zhang, Y.X., Zheng, G.J., et al., 2019a. Rapid transition in winter aerosol composition in Beijing from 2014 to 2017: response to clean air actions. Atmos. Chem. Phys. 19, 11485–11499.

Li, K., Jacob, D.J., Liao, H., Shen, L., Zhang, Q., Bates, K.H., 2019b. Anthropogenic drivers of 2013-2017 trends in summer surface ozone in China. Proc. Natl. Acad. Sci. USA 116, 422–427.

Liu, T., Wang, X., Deng, W., Zhang, Y., Chu, B., Ding, X., et al., 2015. Role of ammonia in forming secondary aerosols from gasoline vehicle exhaust. Sci. China Chem. 58, 1377–1384.

Liu, X.G., Li, J., Qu, Y., Han, T., Hou, L., Gu, J., et al., 2013. Formation and evolution mechanism of regional haze: a case study in the megacity Beijing, China. Atmos. Chem. Phys. 13, 4501–4514.

Meng, Z.Y., Lin, W.L., Jiang, X.M., Yan, P., Wang, Y., Zhang, Y.M., et al., 2011. Characteristics of atmospheric ammonia over Beijing, China. Atmos. Chem. Phys. 11, 6139–6151.

Rohde, R.A., Muller, R.A., 2015. Air pollution in China: mapping of concentrations and sources. PLoS ONE 10.

Russell, A.G., McCue, K.F., Cass, G.R., 1988. Mathematical-modeling of the formation of nitrogen-containing pollutants. 2. Evaluation of the effect of emission controls. Environ. Sci. Technol. 22, 1336–1347.

Seinfeld, J.H., Pandis, S.N., 2006. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, 2nd ed. John Wiley & Sons, Inc., New York.

Shi, X.Q., Zhao, C.F., Jiang, J.H., Wang, C.Y., Yang, X., Yung, Y.L., 2018. Spatial representativeness of $PM_{2.5}$ concentrations obtained using observations from network stations. J. Geophys. Res.- Atmos. 123, 3145–3158.

Sun, Y.L., Wang, Z.F., Wild, O., Xu, W.Q., Chen, C., Fu, P.Q., et al., 2016. "APEC blue": secondary aerosol reductions from emission controls in Beijing. Sci. Rep. 6, 20668.

Wang, P., Chen, K., Zhu, S., Wang, P., Zhang, H., 2020. Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. Resour. Conserv. Recycl. 158, 104814.

Wang, T., Nie, W., Gao, J., Xue, L.K., Gao, X.M., Wang, X.F., et al., 2010. Air quality during the 2008 Beijing Olympics: secondary pollutants and regional impact. Atmos. Chem. Phys. 10, 7603–7615.

Wen, L., Xue, L., Wang, X., Xu, C., Chen, T., Yang, L., et al., 2018. Summertime fine particulate nitrate pollution in the North China Plain: increasing trends, formation mechanisms and implications for control policy. Atmos. Chem. Phys. 18, 11261–11275.

Wu, H.J., Tang, X., Wang, Z.F., Wu, L., Lu, M.M., Wei, L.F., et al., 2018. Probabilistic automatic outlier detection for surface air quality measurements from the China national environmental monitoring network. Adv. Atmos. Sci. 35, 1522–1532.

Xing, J., Zhang, Y., Wang, S., Liu, X., Cheng, S., Zhang, Q., et al., 2011. Modeling study on the air quality impacts from emission reductions and atypical meteorological conditions during the 2008 Beijing Olympics. Atmos. Environ. 45, 1786–1798.

Xu, W., Liu, X.J., Liu, L., Dore, A.O., Tang, A.H., Lu, L., et al., 2019. Impact of emission controls on air quality in Beijing during

APEC 2014: Implications from water-soluble ions and carbonaceous aerosol in $PM_{2.5}$ and their precursors. Atmos. Environ. 210, 241–252.
Xue, J., Yuan, Z.B., Griffith, S.M., Yu, X., Lau, A.K.H., Yu, J.Z., 2016. Sulfate formation enhanced by a cocktail of high NO_x, SO_2, particulate matter, and droplet pH during haze-fog events in megacities in China: an observation-based modeling investigation. Environ. Sci. Technol. 50, 7325–7334.
Zhang, M., Wang, X.M., Chen, J.M., Cheng, T.T., Wang, T., Yang, X., et al., 2010. Physical characterization of aerosol particles during the Chinese New Year's firework events. Atmos. Environ. 44, 5191–5198.
Zhang, R., Zhang, Y., Lin, H., Feng, X., Fu, T.-M., Wang, Y., 2020. NOx emission reduction and recovery during COVID-19 in east China. Atmosphere (Basel) 11, 433.
Zheng, B., Tong, D., Li, M., Liu, F., Hong, C., Geng, G., et al., 2018. Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. Atmos. Chem. Phys. 18, 14095–14111.