Influence of COVID-19 Event on Air Quality and their Association in Mainland China

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ABSTRACT

The outbreak of 2019 novel coronavirus (COVID-19) has hugely impacted the world and becomes a global public threat. To prevent the spread of COVID-19, human activities are largely restricted in China in early February, 2020. The influence of strict COVID-19 control policies on air quality and the potential influence of particulate matter concentration on COVID-19 infection in China are of great interest. This study analyzes the concentrations of six major air pollutants in 366 urban areas across mainland China during January 1 to April 30 in 2017–2020. Results show that strict COVID-19 control policies have significantly improved the air quality in many provinces. Compared to 2019, national mean concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂ and CO in 2020 decrease by 14%, 15%, 12%, 16% and 12%, respectively, while the concentration of O₃ increases by 9%. Generally, the diurnal variation of PM_{2.5} and PM₁₀ concentrations remains unchanged during COVID-19 and their concentrations are high in the morning and evening while low in the afternoon. Correlation analysis shows that daily COVID-19 infections are positively correlated with PM_{2.5} concentration in many provinces, indicating a potential risk of aerosol transmission in high PM_{2.5} environment. Thus it is suggested to stay at home in highly polluted days and go out in the afternoon to reduce the risk of infection due to aerosol transmission.

Keywords: COVID-19; Air quality; PM_{2.5}; China.

INTRODUCTION

A novel and contagious pneumonia broke out in the late of 2019. Then it has been identified as a novel strain of coronavirus, which belongs to the same virus family of acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS) (Zheng *et al.*, 2020). This novel coronavirus is named as 2019 novel coronavirus (2019-nCoV) in January 13 and then as coronavirus disease 2019 (COVID-19) in March 6 by World Health Organization (WHO). From early medical reports in middle January, COVID-19 can be transmitted from human to human (Guo *et al.*, 2020; Shereen *et al.*, 2020). In China, the government immediately takes nationwide contingency plans to shut down the traffic and public activities and almost everyone is isolated at home. On June 5, 2020, over 6450000 confirmed cases and over 382000 death are reported by the National Health Commission around the world.

Air pollution is one of the major concerns around the world, especially in developing countries like China and India (Dong *et al.*, 2019). Severe air pollution is a major health risk and can lead to large premature mortality (Schraufnagel

et al., 2019). Previous studies have shown that PM_{2.5} has an adverse impact on human health and long-term exposure to high PM_{2.5} concentration environment will lead to various respiratory diseases because -PM_{2.5} carries lots of harmful matters and viruses and can go directly into our lungs (Hayes *et al.*, 2019; McGuinn *et al.*, 2019). As reported in the 6th Edition of COVID-19 Treatment Regimen (Trial Implementation) published by the National Health Commission of the People's Republic of China, COVID-19 is mainly transmitted by direct contact and droplet transmission, and aerosol transmission is also a potential way (Wang and Du, 2020). The strict COVID-19 control measures implemented in China in the beginning of February aim to minimize the social contact to stop the spread of COVID-19 and results show that these control measures work very well (Kraemer *et al.*, 2020). For example, Xu *et al.* (2020a) investigated the impact of COVID-19 epidemic prevention and control actions on air quality of three cities in Hubei province and found that the average concentrations of PM_{2.5}, PM₁₀, SO₂, CO and NO₂ in February 2020 were much lower than those in February 2017–2019 with an average reduction of 30.1%, 40.5%, 33.4%, 27.9% and 61.4%, respectively. A similar decrease was also reported in Anqing, Hefei, and Suzhou in February 2020 and the overall decreases for PM_{2.5}, PM₁₀, SO₂, CO and NO₂ are 46.5%, 48.9%, 52.5%, 36.2% and 52.8%, respectively compared to those in the same month in 2017–2019 (Xu *et al.*, 2020b). To understand the influence

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of strict control policy on air quality, it is necessary to gain a full view of how much improvement is made on air quality by these COVID-19 control measures across China. Also, current studies have shown that COVID-19 transmission is associated with temperature and humidity (Ma *et al.*, 2020; Xie and Zhu, 2020), however, the potential influence of PM_{2.5} on COVID-19 is still not clear and it might be important for policy makers to implement proper measures to limit the spread of COVID-19 due to aerosol transmission.

In this study, the concentration of six major air pollutions (PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃) measured in 366 urban areas in mainland China during COVID-19 is compared to previous years. The diurnal variations of particulate matter in 31 provinces during February to April are then analyzed. We also explore the potential correlation between PM_{2.5} concentrations and COVID-19 infections and give some suggestions to the public to minimize the risk of COVID-19 infections due to aerosol transmission.

DATA AND METHODS

Data Collection

In this study, a total number of 366 urban area in mainland China is used for the comparison of air quality. The air quality data used here are the hourly concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃ as well as air quality index (AQI). The AQI is a dimensionless index describing the air quality (the lower the better). It is the maximum of sub-AQI of the above-mentioned six major pollutants (Eqs. (1) and (2)). The daily AQI is calculated from the 24-hour average of PM_{2.5}, PM₁₀, SO₂, NO₂, CO, and the daily maximum 8-hour O₃ (Xu *et al.*, 2020a). All these data can be obtained from China's National Environmental Monitoring Center (<http://www.cnemc.cn>). The time range of the air quality data is from January to April in 2017 to 2020.

$$SAQI_p = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} (C_p - C_{low}) + I_{low} \quad (1)$$

$$AQI = \max(SAQI_1, SAQI_2, \dots, SAQI_p) \quad (2)$$

where $SAQI_p$ represents the sub-AQI; C_p denotes the concentration of pollutant p ; C_{low} and C_{high} are the concentration breakpoints lower and higher than C_p , respectively; I_{low} and I_{high} are the index breakpoint corresponding to C_{low} and C_{high} , respectively.

The daily counts of confirmed COVID-19 cases in all these 366 urban areas across mainland China are collected from an open Github project called Wuhan-2019-nCov, which provides the up-to-date COVID-19 statistics across the world. The data is crawled from official reports and detailed information and COVID-19 data can be found at <https://github.com/canghailan/Wuhan-2019-nCoV/blob/master/Wuhan-2019-nCoV.json>. The time range of the COVID-19 data is same as the air quality data.

Statistical Analysis

A decrease ratio is defined as $DR = 1 - X_{2020}/X_{2019}$, where

X denotes the average concentration of air pollutant and the subscript represents the year. And this ratio shows the degree of major pollutant reduction due to COVID-19 control policies.

The relationship between daily COVID-19 infections and particulate matter concentration may exhibit spatial variation due to changing aerosol source, control policy and other factors. To represent the varying COVID-19 – PM relationship, we use a mixed effects model to analyze the influence of PM concentration on COVID-19 infections. The mixed effects model estimates daily COVID-19 infections for each site i of day j (COVID _{i,j}) from corresponding PM concentration (PM _{i,j}) in the form of

$$\log(\text{COVID}_{i,j}) = (\alpha + \mu_i) + (\beta + v_i) \overline{PM}_{i,j} + \varepsilon_{i,j}, \quad (\mu_k, v_k) \sim N[(00), \Sigma] \quad (3)$$

$$\overline{PM}_{i,j} = \frac{PM_{i,j} - \text{mean}(PM)}{\text{sd}(PM)} \quad (4)$$

where α and β are the fixed intercept and slope independent of time and location, and μ_i and v_i are the random intercept and slope for each site. The random terms (μ_i and v_i) are sites term which reflects the spatial difference of the COVID-19 – PM relationship due to differences in site specific characteristics like aerosol sources, topography, population density, meteorology, etc. $\overline{PM}_{i,j}$ is the scaled PM concentration, and $\text{mean}(PM)$ and $\text{sd}(PM)$ represents the overall mean PM and its standard deviation. $\varepsilon_{i,j}$ and Σ denote the error term and the variance-covariance matrix for the day-specific random effects. Only matchups with daily COVID-19 infection number ≥ 1 are included in this mixed effect model analysis and the total number of matchups during the studying period is 4351.

RESULTS AND DISCUSSION

Site-scale Analysis of Air Pollutants

Table 1 shows the ambient air quality standard from the Ministry of Ecology and Environment of the People's Republic of China (MEE) and the World Health Organization (WHO). The MEE Level I standard is designed for natural reserve and tourist attractions and Level II is for industrial, residence and rural areas. In general, WHO standards for 24h average PM_{2.5} (25 $\mu\text{g m}^{-3}$), SO₂ (20 $\mu\text{g m}^{-3}$), and NO₂ (40 $\mu\text{g m}^{-3}$) are lower than MEE Level I standards (35 $\mu\text{g m}^{-3}$, 50 $\mu\text{g m}^{-3}$, and 80 $\mu\text{g m}^{-3}$). The MEE Level I standards for 24 h average PM₁₀ (50 $\mu\text{g m}^{-3}$) and O₃ (100 $\mu\text{g m}^{-3}$) are in consistent with WHO standards.

Fig. 1 shows the site-scale concentrations of six major pollutants in February 2017–2019 and February 2020. For 24 h average PM_{2.5} and PM₁₀, only the cities in Tibet and Yunnan as well as some northern cities in Heilongjiang meet the WHO and MEE Level I standard in February 2017–2019, and due to the strict control policy in February 2020, many cities in south China meet the standards and the spatial

Table 1. Ambient air quality standard from the World Health Organization (WHO) and the Ministry of Ecology and Environment of the People's Republic of China (MEE).

Pollutants	WHO		MEE			unit
	Time range	Value	Time range	Level I	Level II	
PM _{2.5}	24 h	25	24 h	35	75	$\mu\text{g m}^{-3}$
PM ₁₀	24 h	50	24 h	50	150	$\mu\text{g m}^{-3}$
SO ₂	24 h	20 (7.6)	24 h	50 (18.9)	150 (56.8)	$\mu\text{g m}^{-3}$ (ppb)
NO ₂	1 year	40 (21.1)	24 h	80 (42.3)	80 (42.2)	$\mu\text{g m}^{-3}$ (ppb)
O ₃	8 h	100 (50.5)	8 h	100 (50.5)	160 (80.8)	$\mu\text{g m}^{-3}$ (ppb)
CO	-	-	24 h	4 (3.5)	4 (3.5)	mg m^{-3} (ppm)

Note: concentration (ppb) = $24.45 \div \text{Molecular weight} \times \text{concentration} (\mu\text{g m}^{-3})$; concentration (ppm) = $24.45 \div \text{Molecular weight} \times \text{concentration} (\text{mg m}^{-3})$; concentration with unit of ppb or ppm is shown in the parenthesis. Level I is for natural reserve and tourist attractions. Level II is for industrial, residence and rural areas.

Fig. 1. Monthly mean concentration of PM_{2.5}, PM₁₀, SO₂, NO₂, O₃, and CO in (a, c, e, g, i, k) February 2017–2020 and (b, d, f, h, j, l) February 2020.

Fig. 1. (continued).

area showing MEE Level II standard decreases significantly. For 24 h average SO_2 , most cities across China meet the WHO and MEE Level I standard and only several cities in Shanxi exceed the WHO and MEE Level I standard in February 2017–2019, and in February 2020 all of the cities including cities in Shanxi meet the standard. NO_2 concentrations in Beijing, Tianjin, Hebei, Shanxi, Shaanxi, Shandong Jiangsu and Xinjiang are observed over the WHO and MEE Level I standard concentration in February 2017–2019 and similar to SO_2 , all the cities meet the standard in February 2020. O_3 concentrations in most part of China generally meet the WHO and MEE Level I standard except some coastal cities and remote region and the spatial characteristic changes little in February 2020. All of CO

concentrations across China meet the WHO and MEE Level I standard in February 2017–2019 and in February 2020.

$\text{PM}_{2.5}$, PM_{10} , SO_2 , NO_2 and CO are concentrated mainly in the north part of China, especially Beijing-Tianjin-Hebei region, where their concentrations in February 2017–2019 are around $100 \mu\text{g m}^{-3}$, $160 \mu\text{g m}^{-3}$, $40 \mu\text{g m}^{-3}$, $60 \mu\text{g m}^{-3}$, and 1.8 mg m^{-3} , respectively. The spatial distribution of high O_3 concentration is contrary to that of $\text{PM}_{2.5}$, PM_{10} , SO_2 , NO_2 and CO because heterogeneous reactions largely reduced surface O_3 in polluted regions of China (Li et al., 2018; Li et al., 2019a). The O_3 concentration in Beijing-Tianjin-Hebei region is around $60 \mu\text{g m}^{-3}$ in February 2017–2019. Fig. S1 shows the monthly variation of six major pollutant concentrations in February during 2017 to 2020. From Fig. S1,

a decrease trend of the concentration of PM_{2.5}, PM₁₀, SO₂, NO₂ and CO is observed but the decrease trend is mild. While in February 2020, a sharp fall of the concentration of PM_{2.5}, PM₁₀, SO₂, NO₂ and CO is observed across the whole country. In Beijing-Tianjin-Hebei region, the PM_{2.5}, PM₁₀, SO₂, NO₂ and CO concentrations decrease from 100 $\mu\text{g m}^{-3}$, 150 $\mu\text{g m}^{-3}$, 20 $\mu\text{g m}^{-3}$, 40 $\mu\text{g m}^{-3}$, and 1.2 mg m^{-3} in February 2019 to 70 $\mu\text{g m}^{-3}$, 80 $\mu\text{g m}^{-3}$, 10 $\mu\text{g m}^{-3}$, 25 $\mu\text{g m}^{-3}$, and 0.5 mg m^{-3} in February 2020, respectively. Such a pollutant reduction is directly related to the strict COVID-19 control measures, because the measures restrict many of the public transport, production and business activities and minimize almost all kinds of social activities that may cause direct contact between people.

To take a further look at air quality variation between months, we compare the PM_{2.5} concentration from January to April in 2019 and 2020 (Fig. 2). Before the implementation of strict COVID-19 control policy at the beginning of February 2020, an identical spatial distribution of PM_{2.5} is observed in January 2020 compared to January 2019. The high concentration of PM_{2.5} in wintertime is mostly due to the large amount of anthropogenic pollutants emitted from heating, industry and traffic and also due to the adverse weather conditions in favor of the massive accumulation of pollutants (Deng *et al.*, 2019; Yang *et al.*, 2019). As time goes, the intensification of atmospheric movements accelerates the diffusion of pollutants and a decrease trend of PM_{2.5} concentration from January to April is found (Su *et al.*, 2017; Li *et al.*, 2019b). For example in Tianjin, the monthly mean PM_{2.5} concentrations from January to April 2019 are 81 $\mu\text{g m}^{-3}$, 78 $\mu\text{g m}^{-3}$, 54 $\mu\text{g m}^{-3}$, and 49 $\mu\text{g m}^{-3}$, respectively, and those from January to April 2020 are 102 $\mu\text{g m}^{-3}$, 62 $\mu\text{g m}^{-3}$, 43 $\mu\text{g m}^{-3}$, and 40 $\mu\text{g m}^{-3}$, respectively. In April 2020, the PM_{2.5} concentration in most part of China has been significantly decreased compared to 2019. However, PM_{2.5} concentration in Northeast China met an increase. For example in Harbin, the PM_{2.5} concentration increases from 36 $\mu\text{g m}^{-3}$ in April 2019 to 91 $\mu\text{g m}^{-3}$ in April 2020. This is mostly due to the slowdown of the COVID-19 control policy, and farmers went out and burned their straw, which led to the significant increase of PM_{2.5} concentration. The adverse weather condition also contributes to this increase (Li *et al.*, 2016; Yin *et al.*, 2017).

Provincial-scale Analysis of Air Pollutants

Table 2 shows the decrease ratios of the provincial mean air pollutant concentrations during February to April in 2020 compared to 2019. For PM_{2.5}, an overall decrease ratio of 14% is observed on national scale. There are 12 provinces showing a decrease ratio over 20% including Tianjin (20%), Hebei (29%), Shanxi (24%), Shanghai (21%), Jiangsu (31%), Zhejiang (22%), Anhui (30%), Shandong (29%), Henan (33%), Hubei (23%), Shaanxi (22%), and Qinghai (22%). For example in Shanghai, Hubei and Qinghai, the PM_{2.5} concentrations decrease from 50 $\mu\text{g m}^{-3}$, 27 $\mu\text{g m}^{-3}$, and 49 $\mu\text{g m}^{-3}$ in February–April 2019 to 39 $\mu\text{g m}^{-3}$, 21 $\mu\text{g m}^{-3}$, and 38 $\mu\text{g m}^{-3}$ in February–April 2020, respectively. Insignificant decrease of PM_{2.5} concentration (DR < 5%) is observed in Jiangxi (5%), Guangdong (4%), Guangxi (0%), Chongqing (5%), and

Gansu (4%). And there are three provinces showing a slight increase of PM_{2.5} concentration including Guizhou (9%), Yunnan (6%), and Xinjiang (3%), where the PM_{2.5} concentrations increase from 27 $\mu\text{g m}^{-3}$, 32 $\mu\text{g m}^{-3}$ and 64 $\mu\text{g m}^{-3}$ in February–April 2019 to 30 $\mu\text{g m}^{-3}$, 34 $\mu\text{g m}^{-3}$ and 66 $\mu\text{g m}^{-3}$ in February–April 2020.

Similar to PM_{2.5}, the average PM₁₀ concentration decreases by 15% during February to April 2020 compared to that in 2019. There are 12 provinces showing a decrease ratio over 20% including Beijing (27%), Tianjin (28%), Hebei (30%), Shanxi (21%), Jilin (25%), Heilongjiang (28%), Shanghai (21%), Jiangsu (27%), Anhui (22%), Shandong (30%), Henan (29%), and Hubei (25%). In Hebei, Heilongjiang and Shandong, the PM₁₀ concentrations decrease from 114 $\mu\text{g m}^{-3}$, 73 $\mu\text{g m}^{-3}$, and 109 $\mu\text{g m}^{-3}$ in February–April 2019 to 80 $\mu\text{g m}^{-3}$, 52 $\mu\text{g m}^{-3}$, and 77 $\mu\text{g m}^{-3}$ in February–April 2020, respectively. The decrease ratios for PM₁₀ in Beijing, Jilin and Heilongjiang are much larger than those for PM_{2.5}, and this is probably due to the weaker dust transport in 2020 compared to 2019. Five provinces shows an insignificant variation of PM₁₀ concentration, which are Jiangxi (3%), Guangdong (4%), Guangxi (2%), Hainan (4%), and Guizhou (2%). Only Gansu and Xinjiang meet an increase of PM₁₀ concentration by 3% and 8%, where the PM₁₀ concentrations increase from 84 $\mu\text{g m}^{-3}$ and 86 $\mu\text{g m}^{-3}$ in 2019 to 174 $\mu\text{g m}^{-3}$ and 188 $\mu\text{g m}^{-3}$ in.

The national average decrease ratio for SO₂ is 12%. Around half of mainland China (14 of 31 provinces involved in this study) has a decrease ratio between 10% and 20%. Only 6 provinces show a decrease ratio over 20%, which includes Beijing (28%), Tianjin (30%), Hebei (27%), Shanxi (25%), Liaoning (27%), and Shandong (22%), and their SO₂ concentrations decrease from 5 $\mu\text{g m}^{-3}$, 12 $\mu\text{g m}^{-3}$, 17 $\mu\text{g m}^{-3}$, 27 $\mu\text{g m}^{-3}$, 23 $\mu\text{g m}^{-3}$ and 15 $\mu\text{g m}^{-3}$ in February–April 2019 to 4 $\mu\text{g m}^{-3}$, 9 $\mu\text{g m}^{-3}$, 12 $\mu\text{g m}^{-3}$, 20 $\mu\text{g m}^{-3}$, 17 $\mu\text{g m}^{-3}$ and 11 $\mu\text{g m}^{-3}$ in February–April 2020, respectively. Five provinces show an increase of SO₂ concentrations during COVID-19, and they are Heilongjiang (2%), Jiangxi (6%), Hubei (1%), Guangdong (3%), and Tibet (32%). In Jiangxi and Tibet, the SO₂ concentrations increase from 11 $\mu\text{g m}^{-3}$ and 5 $\mu\text{g m}^{-3}$ in February–April to 12 $\mu\text{g m}^{-3}$ and 7 $\mu\text{g m}^{-3}$ in February–April 2020. The significant increase of SO₂ may result from the biomass burning emission transported from India during the pre-monsoon period (Cong *et al.*, 2015).

The largest decrease ratio (16%) on national scales is observed in NO₂ concentration. Around 70% of the country (22 of 31 provinces involved in this study) has a decrease ratio between 10% and 20%. Five provinces show a decrease ratio over 20% including Beijing (31%), Hebei (22%), Shanghai (20%), Shandong (24%), and Hubei (32%), where the NO₂ concentrations decrease from 36 $\mu\text{g m}^{-3}$, 37 $\mu\text{g m}^{-3}$, 39 $\mu\text{g m}^{-3}$, 34 $\mu\text{g m}^{-3}$ and 28 $\mu\text{g m}^{-3}$ in February–April 2019 to 25 $\mu\text{g m}^{-3}$, 29 $\mu\text{g m}^{-3}$, 31 $\mu\text{g m}^{-3}$, 25 $\mu\text{g m}^{-3}$ and 19 $\mu\text{g m}^{-3}$ in February–April 2020, respectively. Only Guangxi and Qinghai show an insignificant decrease of NO₂ by 1% and 5%, respectively, and no increase is observed.

The national scale decrease ratio of CO is 12%, which is similar to SO₂. There are 15 provinces showing a decrease ratio between 10% and 20%. Six provinces show a decrease

Fig. 2. Monthly variation of $\text{PM}_{2.5}$ concentration during (a, c, e, g) January–April 2019 and (b, d, f, h) January–April 2020 in mainland China.

Table 2. Decrease ratio of the provincial mean concentrations of six air pollutants during COVID-19 event (Feb–Apr, 2020) in mainland China.

Province				Decrease ratio (DR)						
	Full name	Abbr.	Code	PM _{2.5}	PM ₁₀	SO ₂	NO ₂	O ₃	CO	AQI
1	Beijing	BJ	11	0.16	0.27	0.28	0.31	−0.12	0.10	0.17
2	Tianjin	TJ	12	0.20	0.28	0.30	0.18	−0.09	0.20	0.20
3	Hebei	HE	13	0.29	0.30	0.27	0.22	−0.06	0.17	0.25
4	Shanxi	SX	14	0.24	0.21	0.25	0.13	−0.01	0.23	0.19
5	Inner Mongolia	IM	15	0.12	0.18	0.08	0.16	−0.03	0.04	0.12
6	Liaoning	LN	21	0.17	0.19	0.27	0.19	−0.05	0.13	0.14
7	Jilin	JL	22	0.12	0.25	0.07	0.12	−0.07	0.03	0.17
8	Heilongjiang	HL	23	0.13	0.28	−0.02	0.19	−0.09	0.00	0.20
9	Shanghai	SH	31	0.21	0.21	0.18	0.20	−0.06	0.12	0.18
10	Jiangsu	JS	32	0.31	0.27	0.15	0.18	−0.11	0.15	0.25
11	Zhejiang	ZJ	33	0.22	0.14	0.11	0.12	−0.18	0.17	0.13
12	Anhui	AH	34	0.30	0.22	0.14	0.18	−0.13	0.17	0.23
13	Fujian	FJ	35	0.10	0.08	0.16	0.17	−0.18	0.21	0.04
14	Jiangxi	JX	36	0.05	0.03	−0.06	0.06	−0.30	0.18	0.02
15	Shandong	SD	37	0.29	0.30	0.22	0.24	−0.03	0.20	0.25
16	Henan	HA	41	0.33	0.29	0.16	0.18	−0.03	0.18	0.27
17	Hubei	HB	42	0.23	0.25	−0.01	0.32	−0.22	0.03	0.20
18	Hunan	HN	43	0.11	0.11	0.08	0.14	−0.10	0.16	0.09
19	Guangdong	GD	44	0.04	0.04	−0.03	0.11	−0.23	0.21	0.00
20	Guangxi	GX	45	0.00	0.02	0.06	0.01	−0.23	0.16	−0.01
21	Hainan	HI	46	0.06	0.04	0.14	0.16	−0.34	−0.01	0.00
22	Chongqing	CQ	50	0.05	0.08	0.12	0.12	0.08	0.07	0.05
23	Sichuan	SC	51	0.09	0.08	0.15	0.14	−0.06	0.10	0.06
24	Guizhou	GZ	52	−0.09	0.02	0.06	0.19	−0.07	0.07	−0.05
25	Yunnan	YN	53	−0.06	0.10	0.19	0.12	−0.01	0.00	0.00
26	Tibet	XZ	54	0.16	0.17	−0.32	0.17	−0.03	−0.03	0.07
27	Shaanxi	SN	61	0.22	0.17	0.17	0.14	−0.05	0.24	0.17
28	Gansu	GS	62	0.04	−0.03	0.12	0.10	0.03	0.11	0.00
29	Qinghai	QH	63	0.22	0.14	0.14	0.05	0.02	0.10	0.10
30	Ningxia	NX	64	0.12	0.12	0.11	0.12	−0.01	0.19	0.12
31	Xinjiang	XJ	65	−0.03	−0.08	0.09	0.23	−0.11	0.09	−0.04
National average DR				0.14	0.15	0.12	0.16	−0.09	0.12	0.11

Note: $DR = 1 - X_{2020}/X_{2019}$, where X denotes the concentration of air pollutants and the subscript represents the year.

ratio over 20%, which includes Tianjin (20%), Shanxi (23%), Fujian (21%), Shandong (21%), Guangdong (21%), and Shaanxi (24%). Their CO concentrations decrease from 1.0 mg m^{−3}, 1.1 mg m^{−3}, 0.7 mg m^{−3}, 0.9 mg m^{−3} and 0.9 mg m^{−3} in February–April 2019 to 0.8 mg m^{−3}, 0.9 mg m^{−3}, 0.6 mg m^{−3}, 0.7 mg m^{−3} and 0.7 mg m^{−3} in February–April 2020, respectively. Inner Mongolia, Jilin, Heilongjiang, Hubei, and Yunnan show an insignificant decrease of CO concentration with a decrease ratio of 4%, 3%, 0, 3% and 0, respectively. Only Hainan and Tibet show an increase of CO concentration of 1% and 3%, respectively, where the CO concentrations in February–April 2020 are 0.5 mg m^{−3} and 0.6 mg m^{−3}.

The variation of O₃ concentration is generally the opposite of other pollutants and it shows an increase of 9% on national scale. There are 28 provinces show an increase of O₃ concentration. Five provinces have an increase ratio over 20% including Jiangxi (30%), Hubei (22%), Guangdong (23%), Guangxi (23%), and Hainan (34%), where the O₃ concentrations increase from 55 µg m^{−3}, 54 µg m^{−3}, 48 µg m^{−3},

40 µg m^{−3} and 48 µg m^{−3} in February–April 2019 to 65 µg m^{−3}, 66 µg m^{−3}, 59 µg m^{−3}, 48 µg m^{−3} and 64 µg m^{−3} in February–April 2020, respectively. And nine provinces show an insignificant increase of O₃ concentration (< 5%), which includes Shanxi (1%), Inner Mongolia (3%), Liaoning (5%), Shandong (3%), Henan (3%), Yunnan (1%), Tibet (3%), Shaanxi (5%), and Ningxia (1%). Three provinces meet a decrease of O₃ concentration including Chongqing (8%), Gansu (3%), and Qinghai (2%), where the O₃ concentrations decrease from 45 µg m^{−3}, 73 µg m^{−3} and 79 µg m^{−3} in 2019 to 42 µg m^{−3}, 71 µg m^{−3} and 77 µg m^{−3} in 2020, respectively.

AQI decreases by 11% on national scale during February to April 2020 compared to 2019. Large decrease ratios (> 20%) are found in Tianjin (20%), Hebei (25%), Heilongjiang (20%), Jiangsu (25%), Anhui (23%), Shandong (25%), Henan (27%) and Hubei (20%), where the AQI decreases from 93, 96, 67, 77, 81, 92, 109, and 73 in 2019 to 75, 72, 54, 58, 62, 69, 80, and 59 in 2020, respectively. There are 10 provinces having a decrease ratio between 10% and 20% and 7 provinces having an insignificant decrease of

AQI ($< 5\%$). Guangxi, Guizhou, and Xinjiang show an increase of AQI by 1%, 5% and 4%, respectively. The variation of AQI is generally in consistent with that of $PM_{2.5}$, PM_{10} , SO_2 , NO_2 and CO, while the opposite of O_3 .

In general, insignificant variation of pollutants are mainly found in Fujian, Jiangxi, Guangdong, Guangxi, Hainan, Guizhou, Yunnan, Gansu, and Xinjiang, where the seasonal mean concentration of major pollutants are generally low, while significant variation of pollutants are mainly observed in Beijing, Tianjin, Hebei, Shandong, Shanghai, Anhui, Jinagsu, Henan, and Hubei, where the seasonal mean

concentration of major pollutants are generally high. Thus, the strict COVID-19 control policy can effectively improve the air quality in northeast and inland provinces where previous air quality was poor, while the effect of the COVID-19 policy is less significant in southeast coastal and western provinces where previous air quality was good. On the whole, twenty six provinces (84%) meet an AQI improvement due to COVID-19 control policy.

Diurnal Variation of $PM_{2.5}$

Fig. 3 shows the diurnal variation of $PM_{2.5}$ concentrations

Fig. 3. Diurnal variation of $PM_{2.5}$ concentration in 2019 and 2020 on (a) national scale and (b–h) provincial scale.

in 2019 and 2020, and Fig. S2 presents results of the rest 24 provinces. In general, $\text{PM}_{2.5}$ concentrations vary with time and region. On national scale, the lowest $\text{PM}_{2.5}$ concentrations ($55 \mu\text{g m}^{-3}$ in February 2020) are distributed in the afternoon while the peak values ($70 \mu\text{g m}^{-3}$) are generally distributed in the morning and evening. Such a variation is mostly observed in provinces like Hebei, Shandong, Henan, Shaanxi, and Heilongjiang, where the daily mean $\text{PM}_{2.5}$ concentration is generally high ($> 50 \mu\text{g m}^{-3}$). However, the variation is less obvious in provinces like Guangdong and Zhejiang, where the daily mean $\text{PM}_{2.5}$ concentration is low ($< 30 \mu\text{g m}^{-3}$). Although strict COVID-19 control policy is implemented, the diurnal variation of $\text{PM}_{2.5}$ remains unchanged. The low $\text{PM}_{2.5}$ concentration in the afternoon is generally due to that the height of boundary layer in the afternoon is the highest of the day, so the concentration is correspondingly decreased to the lowest value (Guo *et al.*, 2017; Li *et al.*, 2019b). When temperature decreases in the evening, the height of boundary layer decreases and accordingly the concentration increases to the peak value. The concentration increase in the morning is mainly due to the rapid increase of aerosol emissions and slow increase of boundary layer height (Guo *et al.*, 2017).

Association between $\text{PM}_{2.5}$ Concentration and COVID-19 Infections

Fig. 4 shows the time series variation of new COVID-19 cases and the total confirmed cases. To better discuss the correlation between $\text{PM}_{2.5}$ concentration and COVID-19 infections, correlations in three time ranges are considered, which are the lockdown (1 February–29 February), main phase (January 20–29 February), and the whole studying period (January 1–30 April). The lockdown refers to the period with nationwide strict COVID-19 control policy, and the main phase refers to the period of the sharp increase of COVID-19 infections. Table 3 shows the statistical results between $\text{PM}_{2.5}$ concentration and the COVID-19 infections in mainland China. The correlations of fixed effect of $\text{PM}_{2.5}$ concentration for lockdown, main phase and the whole studying period are 0.279, 0.200, and 0.199 respectively. Most of the estimated slopes and intercepts have a p-value less than 0.001 and only the estimated slope in main phase has a p-value less than 0.01. The small p-value (< 0.05) and the positive correlations observed in different time ranges indicate that $\text{PM}_{2.5}$ is positively correlated to the new COVID-19 cases, which agrees with the early COVID-19 findings (Xie and Zhu, 2020). To minimize the risk of

Fig. 4. Time series variation of COVID-19 cases in mainland China. Lockdown refers to the period with nationwide strict control policy, and main phase refers to period with sharp increase of total cases.

aerosol transmission, it is not suggested to go out in severe $\text{PM}_{2.5}$ pollution days. And according to the diurnal variation of $\text{PM}_{2.5}$ concentration (Fig. 3), it's better to go out in the afternoon because $\text{PM}_{2.5}$ concentration in the afternoon is generally the lowest of the day. Also, try to avoid going out in late morning and evening because $\text{PM}_{2.5}$ concentration is increasing thus the risk of infections increases.

CONCLUSIONS

This study evaluates the influence of nationwide lockdown on air quality during COVID-19 as well as the association between $\text{PM}_{2.5}$ and COVID-19 infections in mainland China. Data from 366 air quality monitoring stations during January to April in 2017–2020 are used to investigate the air quality improvement. Compared to 2019, a national scale decrease of 14%, 15%, 12%, 16% and 12% is observed for $\text{PM}_{2.5}$, PM_{10} , SO_2 , NO_2 and CO , respectively, while O_3 has a slight increase of 9%. The diurnal variation of particulate matter concentrations changes less during COVID-19. Lowest $\text{PM}_{2.5}$ concentrations are mainly distributed in the afternoon while high concentrations are witnessed in the morning and evening. Correlation analysis shows that positive correlations between $\text{PM}_{2.5}$ concentration and new

Table 3. Statistical results of the fixed effects of $\text{PM}_{2.5}$ concentration on daily COVID-19 infections in mainland China.

Period	N	Slope			Intercept			Correlation of fixed effect
		Estimate	Std. Error	t value	Estimate	Std. Error	t value	
Lockdown Feb 01–Feb 29	2630	0.068***	0.013	5.218	0.331***	0.022	14.748	0.279
Main phase Jan 20–Feb 29	4047	0.027**	0.009	3.114	0.309***	0.020	15.360	0.200
Studying period Jan 01–Apr 30	4351	0.029***	0.009	3.193	0.304***	0.019	16.256	0.199

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

COVID-19 infections are observed in different time ranges. The preliminary results in this study gives the following suggestions to the public to avoid the potential aerosol transmission of COVID-19:

- (1) do not go out in heavy polluted days and try to minimize the exposure time in high PM_{2.5} concentration environment;
- (2) better to go out in the afternoon, because PM_{2.5} concentration is the lowest of a day;
- (3) avoid going out in late morning and evening, because the PM_{2.5} concentration is increasing.

As for policy maker, the increase of PM_{2.5} concentration due to human activities should be avoided, limited or scheduled during this sensitive period to minimize the risk of aerosol transmission of COVID-19. Since the diurnal variation of PM_{2.5} concentration may vary with countries and regions, a further study is planned to suggest a more proper time range for people to go outdoors in other part of world. Also, further studies are needed to understand the detailed knowledge of aerosol transmission of COVID-19 so that more reliable and effective measures can be taken to stop the pandemic.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at <http://www.aaqr.org>.

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