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Impact of the COVID-19 Event on Air Quality in Central China

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ABSTRACT

In early 2020, the COVID-19 epidemic spread globally. This study investigated the air quality of three cities in Hubei Province, Wuhan, Jingmen, and Enshi, central China, from January to March 2017–2020 to analyze the impact of the epidemic prevention and control actions on air quality. The results indicated that in the three cities, during February 2020, when the epidemic prevention and control actions were taken, the average concentrations of atmospheric $PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2 in the three cities were 46.1 μg m^{-3}, 50.8 μg m^{-3}, 2.56 ppb, 0.60 ppm, and 6.70 ppb, and were 30.1%, 40.5%, 33.4%, 27.9%, and 61.4% lower than the levels in February 2017–2019, respectively. However, the average O_3 concentration (23.1, 32.4, and 40.2 ppb) in 2020 did not show a significant decrease, and even increased by 12.7%, 14.3%, and 11.6% in January, February, and March, respectively. This is because a lower concentration of NO_2 resulted in constraints on the NO + O_3 reaction, and the O_3 could not be effectively further depleted. In addition, the average air quality index (AQI) for the three cities in January, February, and March 2020 were 32.2%, 27.7%, and 14.9% lower than the levels in 2017–2019, respectively. Based on the AQIs for the three cities, the combined proportions of Class I and Class II in January, February, and March 2020 increased by 27.9%, 24.8%, and 4.3%, respectively, while the combined proportion of AQI Classes III, IV, V, and VI was reduced from 34.8% to 15.8%. In addition, in the first three months of 2020, the indicatory air pollutants in the three cities for the AQIs were predominant in the following order: $PM_{2.5}$ (72.0%), O_3 (16.4%), PM_{10} (8.3%), NO_2 (2.9%), and CO (0.4%). This study provides useful information for establishing a scientific air pollution control strategy and is a valuable reference for future research on improving urban air quality.

Keywords: COVID-19; AQI; $PM_{2.5}$; PM_{10}; SO_2; CO; NO_2; O_3.

INTRODUCTION

At present, the COVID-19 epidemic that broke out at the end of 2019 continues to spread globally, and the situation is still very serious. On April 12, 2020, globally, there were 1,771,514 COVID-19 confirmed cases and 108,503 deaths (http://www.xinhuanet.com/2020-04/12/c_1125845334.htm).

In order to eliminate the spread of the epidemic, the Chinese government immediately took effective prevention and control actions. On January 24, 2020, Hubei Province government, China, announced the launch of a first-level response to major public health emergencies, which included actions such as quarantining, traffic restrictions, and factory closures, which were immediately implemented. The above prevention and control actions were closely related to the air quality at the time.

The Air Quality Index (AQI) typically reflects the degree of air cleanliness or the level of air pollution and focuses on the assessment of a crowd breathing for a specific period of time (acute or chronic) and the effects of air pollution on their health.

Air quality has become a serious concern of both the Chinese government and the public. Many scholars have conducted air quality assessments in China, reflecting the current problems and proposing control strategies for improvements in air pollution (Wang *et al.*, 2014; Hu *et al.*, 2015; Tong *et al.*, 2016; Lee *et al.*, 2018).

In this study, the air quality of three cities (Wuhan, Jingmen and Enshi) in Hubei Province, central China, including the air pollutants $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3, and AQIs from January to March 2017–2020 were investigated, compared, and discussed. In addition, the impact of the COVID-19 epidemic prevention and control actions on air quality was specifically addressed.

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METHODS

From January to March, 2017-2020, the air quality in three cities in Hubei Province including Wuhan (30°35′N, 114°17′E), Jingmen (31°02′N, 112°12′E) and Enshi Tujia and Miao Autonomous Prefecture (30°16′N, 109°29′E) (abbreviated as Enshi) (Fig. 1), were studied. The air pollutant levels of $PM_{2.5}$, PM_{10}, SO_2, NO_x, CO, and O_3 in these three cities were investigated (http://www.tianqihoubao.com/lishi/).

Wuhan City is located in the eastern part of Hubei Province, in the middle and lower reaches of the Yangtze River Plain, with a subtropical monsoon humid climate. The average temperatures in Wuhan 2017–2020 ranged between –5 and 22℃, between –5 and 25℃, and between 7.4 and 15.2℃, and averaged 4.0, 6.6, and 10.9°C, in January, February and March, respectively.

Jingmen City is located in the central part of Hubei Province, and its entire territory is dominated by mountains, with a subtropical warm monsoon climate. During 2017–2020, the average temperatures in Jingmen ranged from –7℃ to15℃, from –4℃ to 22℃, and from 0℃ to 25℃, and averaged 3.8, 6.1, and 10.3°C, in January, February and March, respectively.

Enshi is located in southwestern Hubei Province and has a subtropical monsoon humid mountain climate. During 2017–2020, the average temperatures in Enshi ranged from –4 to 14℃, from 0 to 19℃, and from 4 to 27℃, and averaged 5.2, 7.1, and 10.9°C, in January, February, and March, respectively.

AIR QUALITY INDEX (AQI)

The AQI is a dimensionless index that quantitatively describes the status of air quality. As indicated in Eq. (1), the sub-AQIs of the six criteria pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and O_3) were first calculated with the observation concentrations. The AQI comes from the maximum of the sub-AQI of all pollutants, as shown in Eq. (2), where when the AQI is higher than 50, contributor of the maximum sub-AQI is defined as the primary pollutant on that day (She *et al.*, 2017; Shen *et al.*, 2017).

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

$$AQI = \max(I_1, I_2, \ldots, I_n) \quad (2)$$

$IAQI_P$: the air quality sub index for air pollutant p;
C_P: the concentration of pollutant p;
C_{low}: the concentration breakpoint that is ≤ C_P;
C_{high}: the concentration breakpoint that is ≥ C_P;
I_{low}: the index breakpoint corresponding to C_{low};
I_{high}: the index breakpoint corresponding to C_{high}.

Ambient air quality is closely related to the development of human society and has a major impact on human health. The AQI simplifies the concentrations of different pollutants into a single numerical value to reflect overall air quality. The daily AQI value is calculated from the 24-hour average concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and the daily maximum 8-hour concentration of O_3.

Class I: 0–50 (Green), Good.
Class II: 51–100 (Yellow), Moderate.
Class III: 101–150 (Orange), Unhealthy for Sensitive Groups.
Class IV: 151–200 (Red), Unhealthy.
Class V: 201–300 (Purple), Very unhealthy.
Class VI: 300–500 (Maroon), Hazardous.

RESULTS AND DISCUSSION

Comparison for Air Pollutants

The average concentrations for $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2, and O_3 in January, February and March 2017–2019 and those of 2020, respectively, are shown and compared in Figs. 2(A)–2(F), respectively.

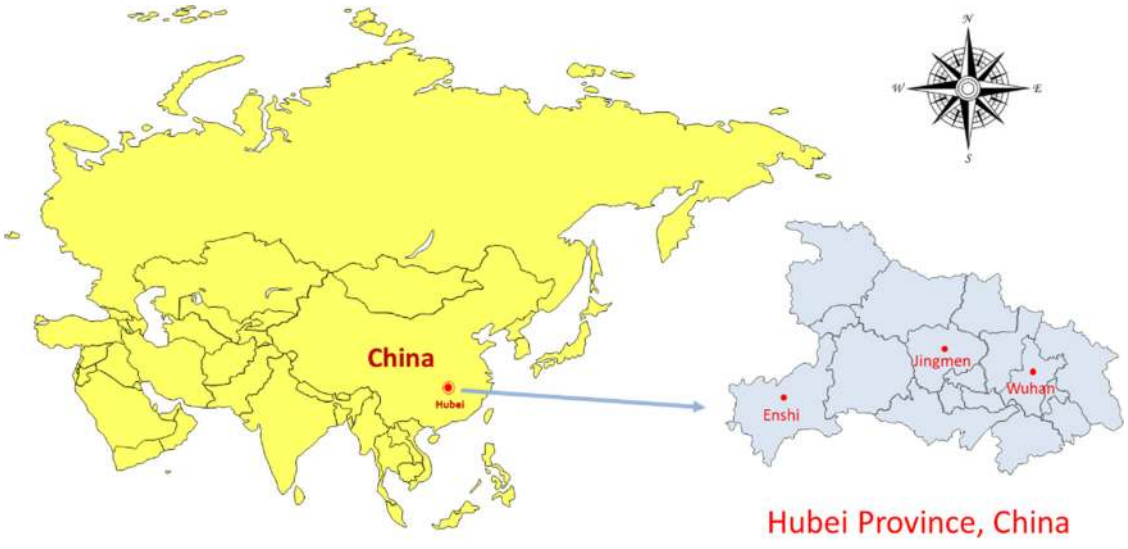

Fig. 1. Location of Wuhan, Jingmen, and Enshi in Hubei Province, China.

Atmospheric particulate matter is a mixture that includes organic components, inorganic ions, mineral dust, and so on. $PM_{2.5}$ refers to atmospheric particles with a particle size of less than 2.5 μm, which are easily accumulated in the human respiratory tract and seriously affect human health. Studies have shown that $PM_{2.5}$ pollution is closely related to human morbidity or mortality (Dockery *et al.*, 1993; Pope III *et al.*, 2002) and that pollution is more severe in winter (Tao *et al.*, 2009; Xu *et al.*, 2017; Ning *et al.*, 2018; Zhao *et al.*, 2018b).

As shown in Fig. 2(A)(a), during January 2017–2019, in Wuhan, Jingmen, and Enshi, the $PM_{2.5}$ concentrations ranged between 17 and 198, 20 and 298, and 22 and 248 μg m^{-3} and averaged 88.8, 115, and 77.1 μg m^{-3}, respectively. Those during January 2020 were in the range of 12–108, 26–146, and 15–70 μg m^{-3}, with averages of 59.6, 87.8, and 36.8 μg m^{-3}, respectively, and were 32.9%, 23.5%, and 52.2% lower than those during January 2017–2019. Based on the data from the three cities, during January 2020, the average $PM_{2.5}$ decreased by 36.2% compared with that in January 2017–2019.

As shown in Fig. 2(A)(b), in Wuhan, Jingmen, and Enshi, during February 2017–2019, the $PM_{2.5}$ concentrations ranged between 16 and 165, 24 and 179, and 12 and 116 μg m^{-3} and averaged 67.9, 82.1, and 51.5 μg m^{-3}, respectively. Those during February 2020 ranged from 9–97, 12–139, and 12–92 μg m^{-3}, averaged 38.0, 57.1, and 43.4 μg m^{-3}, respectively, and were 44.0%, 30.5%, and 15.7% lower than those during February 2017–2019. Based on the data from the three cities, during February 2020, the average $PM_{2.5}$ concentration decreased by 30.1% compared with that in February 2017–2019.

As shown in Fig. 2(A)(c), in Wuhan, Jingmen, and Enshi, during March 2017–2019, the $PM_{2.5}$ concentrations ranged from 23–223, 11–104, and 10–70 μg m^{-3} and averaged 53.1, 51.6, and 35.1 μg m^{-3}, respectively. Those during March 2020 ranged from 8–57, 8–83, and 5–95 μg m^{-3}, and averaged 34.5, 44.3, and 35.7 μg m^{-3}, respectively. Levels in Wuhan and Jingmen were 35.1% and 14.1% lower, respectively, than those during March 2017–2019, but in Enshi, there was a 1.7% increase. Based on the data from the three cities, $PM_{2.5}$ decreased by 15.8% on average compared with March 2017–2019.

It can be seen that the average concentration of $PM_{2.5}$ decreased from January to March 2020. There may be two reasons for this significant reduction in January. The first is that the second half of January 2020 is the lunar New Year holiday in China. As a result, most factories were closed, and the employees were on vacation, which resulted in a significant reduction in industrial emissions. Secondly, since January 23, 2020, Hubei Province has implemented strict epidemic prevention and control actions, which led to traffic stagnation and factory closures, thus greatly reducing both emissions from automobile exhaust and industrial production. The reason for the decrease in $PM_{2.5}$ concentration in February 2020 was due to strict epidemic prevention and control actions. In March, under these actions, $PM_{2.5}$ concentrations in Wuhan and Jingmen still showed a downward trend, but in Enshi, there was an increase of 1.7%. This may be because a better ecological environment in Enshi leads to lower $PM_{2.5}$ levels, and at the same time, the temperature rise in March was more conducive to the dispersion of air pollutants. Therefore, the epidemic prevention and control actions did not have a significant impact on the air quality in Enshi.

PM_{10} refers to atmospheric particulate matter with a diameter of less than 10 microns, mainly derived from industrial exhaust emissions, fossil fuel combustion, motor vehicle exhaust, and dust entrainment (Kong *et al.*, 2011). Airborne particulate pollution is extremely detrimental to human health and affects the human respiratory and nervous systems (Wang and Chen, 2016).

As shown in Fig. 2(B)(a), in Wuhan, Jingmen, and Enshi, during January 2017–2019, the PM_{10} concentrations ranged between 14 and 201, 15 and 251, and 26 and 292 μg m^{-3} and averaged 99.6, 110.3, and 101.1 μg m^{-3}, respectively. Those during January 2020 ranged from 19–135, 10–128, and 21–114 μg m^{-3}, with averages of 69.9, 73.7, and 50.7 μg m^{-3}, respectively, which were 29.8%, 33.2%, and 49.8% lower than those during January 2017–2019. Based on the data from the three cities, during January 2020, the average PM_{10} decreased by 37.6% compared with that in January 2017–2019.

As shown in Fig. 2(B)(b), in Wuhan, Jingmen, and Enshi, during February 2017–2019, the PM_{10} concentrations ranged between 13 and 211, 29 and 218, and 24 and 150 μg m^{-3} and averaged 88.2, 105.0, and 69.6 μg m^{-3}, respectively. Those during February 2020 ranged from 12–103, 13–122, and 21–101 μg m^{-3}, with averages of 46.0, 54.2, and 52.1 μg m^{-3}, respectively, which were 47.9%, 48.4%, and 25.1% lower

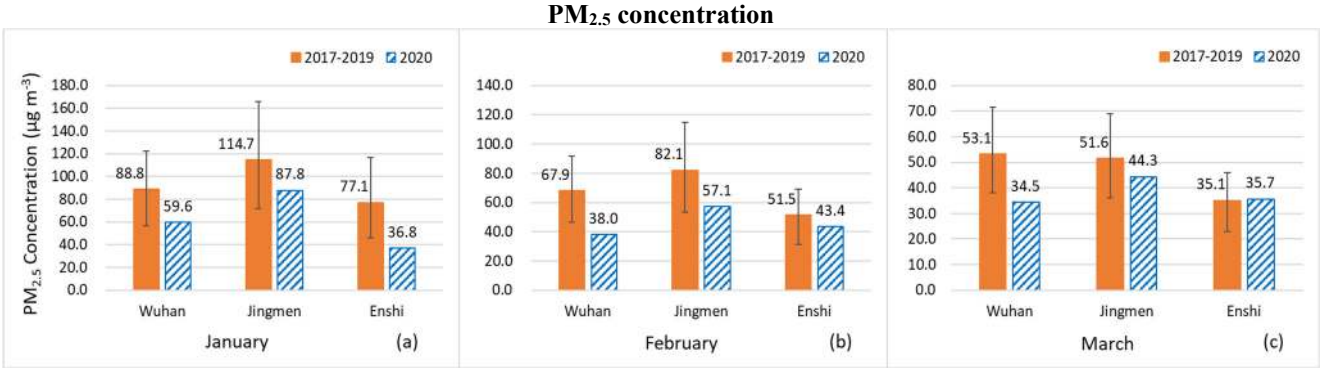

Fig. 2(A). The average $PM_{2.5}$ concentrations during January, February and March 2017–2019 and those of 2020, respectively.

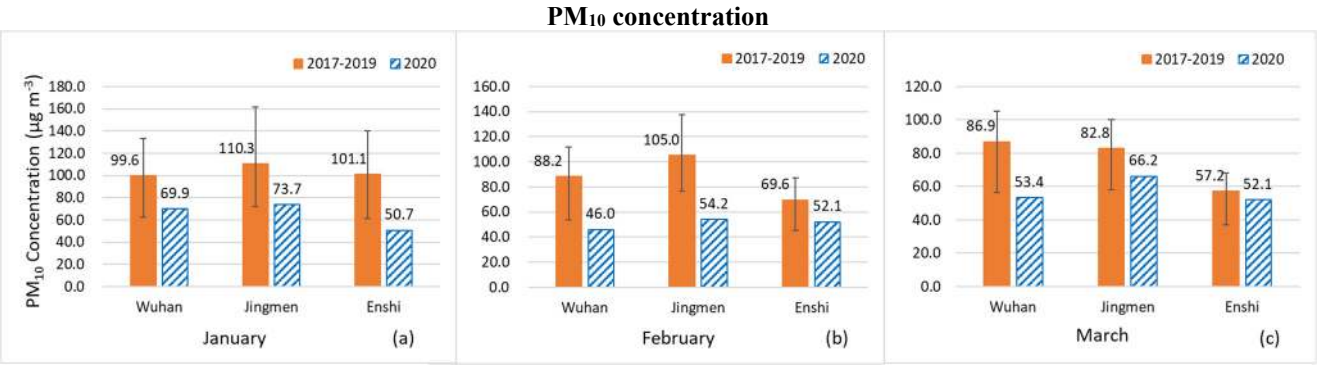

Fig. 2(B). The average concentrations of PM_{10} in January, February, and March 2017–2019 and those of 2020, respectively.

than those during February 2017–2019. Based on the data from the three cities, during February 2020, the average PM_{10} decreased by 40.5% compared with that in February 2017–2019.

As shown in Fig. 2(B)(c), in Wuhan, Jingmen, and Enshi, during March 2017–2019, the PM_{10} concentrations ranged between 21 and 244, 20 and 175, and 11 and 112 μg m^{-3} and averaged 86.9, 82.8, and 57.2 μg m^{-3}, respectively. Those during March 2020 ranged from 13–88, 17–153, and 15–124 μg m^{-3}, with averages of 55.4, 66.2, and 52.1 μg m^{-3}, respectively, which were 38.6%, 20.0%, and 8.9% lower than that of during March 2017–2019. Based on the data from the three cities, during March 2020, the average PM_{10} decreased by 22.5% compared with that in March 2017–2019.

It can be seen that the concentration of PM_{10} decreased significantly from January to March 2020, especially in February when strict prevention and control actions were taken. A decrease in PM_{10} in January 2020 can be attributed to the reduction in construction dust and industrial production emissions during the Lunar New Year holidays. The reduction in February and March can be attributed to the strict implementation of epidemic prevention and control actions, which resulted in a substantial reduction in mobile exhaust emissions.

Artificially generated SO_2 mainly comes from the combustion of coal, petroleum, and chemical fuels. SO_2 in the air is easily oxidized into SO_3, which then develops into acid rain, causing damage to surface vegetation and buildings (Kato *et al.*, 2016).

As shown in Fig. 2(C)(a), in Wuhan, Jingmen, and Enshi, during January 2017–2019, the SO_2 concentrations ranged between 1.40 and 9.45, 2.10 and 15.1, and 1.40 and 11.9 ppb and averaged 3.84, 6.08, and 2.95 ppb, respectively. Those during January 2020 ranged from 1.75–3.85, 2.10–5.95, and 1.40–2.80 ppb, with averages of 2.30, 3.42, and 1.45 ppb, respectively, which were 40.1%, 43.8%, and 51.1% lower than those during January 2017–2019. Based on the data from the three cities, during January 2020, the average SO_2 decreased by 45.0% compared with that in January 2017–2019.

As shown in Fig. 2(C)(b), in Wuhan, Jingmen, and Enshi, during February 2017–2019, the SO_2 concentrations ranged between 1.05 and 9.80, 1.75 and 12.6, and 1.05 and 7.35 ppb and averaged 3.79, 5.47, and 2.28 ppb, respectively. Those during February 2020 ranged from 1.75–4.55, 2.45–5.60, and 1.40–1.75 ppb, with averages of 2.66, 3.56, and 1.47 ppb, respectively, which were 29.9%, 34.9%, and 35.4% lower than those during February 2017–2019. Based on the data from the three cities, during February 2020, the average SO_2 decreased by 33.4% compared with that in February 2017–2019.

As shown in Fig. 2(C)(c), in Wuhan, Jingmen, and Enshi, during March 2017–2019, the SO_2 concentrations ranged between 1.05 and 10.2, 2.10 and 17.2, and 1.05 and 7.10 ppb and averaged 3.56, 5.67, and 2.85 ppb, respectively. Those during March 2020 ranged from 1.75–5.95, 2.10–7.0, and 1.40–2.10 ppb, with averages of 3.14, 3.62, and 1.67 ppb, respectively, which were 11.8%, 36.1%, and 41.3% lower than those during March 2017–2019. Based on the data from the three cities, during March 2020, the average SO_2 decreased by 29.7% compared with that in March 2017–2019.

It can be seen that the SO_2 concentration of the three cities significantly decreased from January to March in 2020, which shows that the suspension of production caused by the Chinese New Year holiday and factory closures due to epidemic prevention and control actions resulted in a significant reduction in SO_2 emissions.

Carbon monoxide (CO) is one of the important indicators of air pollutants that are mainly derived from incomplete combustion activities such as fuel combustion and automobile exhaust emissions related to human activities. High concentrations of CO pose a major threat to human health and can quickly cause hypoxia in humans, leading to dizziness and even death (Scharte *et al.*, 2000; Li *et al.*, 2017).

As shown in Fig. 2(D)(a), in Wuhan, Jingmen, and Enshi, during January 2017–2019, the CO concentrations ranged between 0.48 and 1.76, 0.56 and 1.92, and 0.48 and 1.92 ppm, and averaged 1.03, 1.04, and 0.99 ppm, respectively. Those during January 2020 ranged from 0.40–1.28, 0.48–1.12, and 0.32–0.96 ppm, with averages of 0.79, 0.78, and 0.62 ppm, respectively, which were 23.8%, 25.0%, and 37.6% lower than those of during January 2017–2019. Based on the data from the three cities, during January 2020, the average CO decreased by 28.8% compared with that in January 2017–2019.

As shown in Fig. 2(D)(b), in Wuhan, Jingmen, and Enshi, during February 2017–2019, the CO concentrations ranged between 0.32 and 1.36, 0.56 and 1.12, and 0.32 and 1.12 ppm,

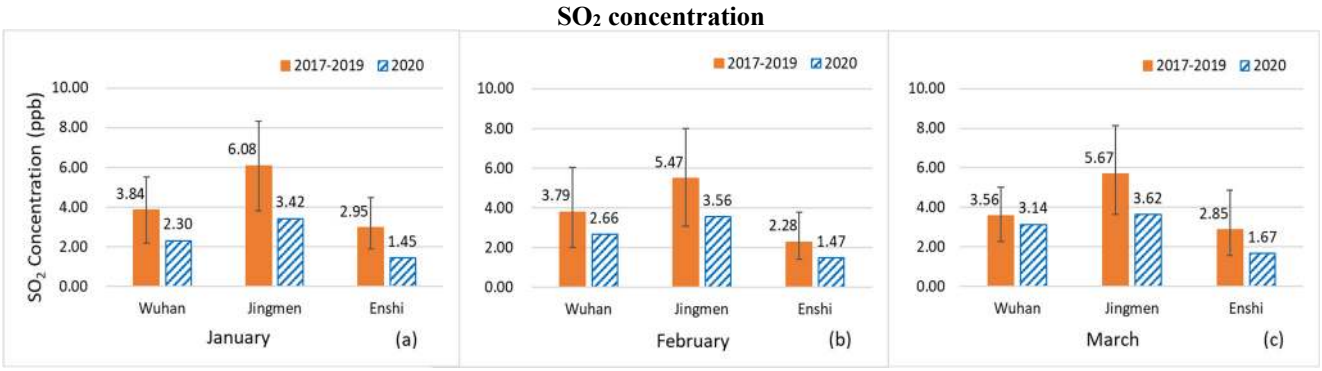

Fig. 2(C). The average concentrations of SO_2 in January, February, and March 2017–2019 and those of 2020, respectively.

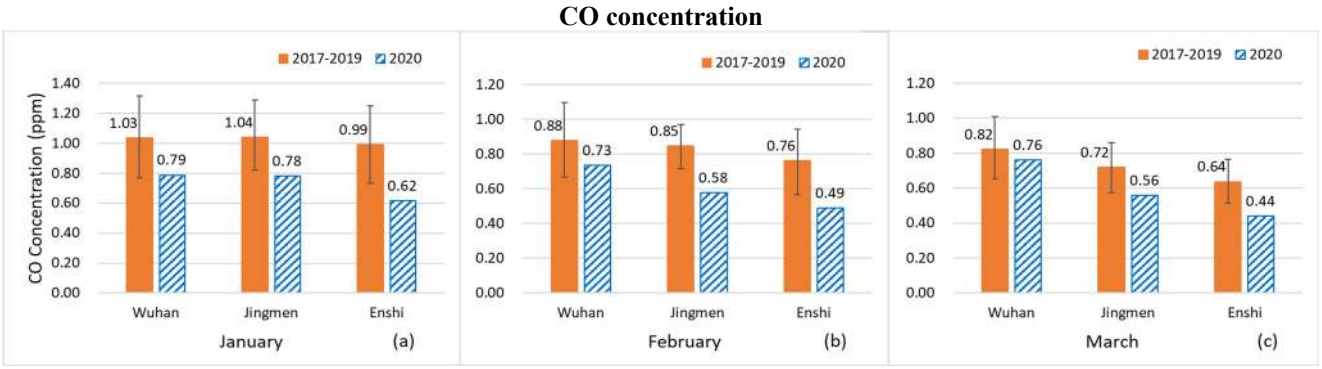

Fig. 2(D). The average concentrations of CO in January, February, and March 2017–2019 and those of 2020, respectively.

and averaged 0.88, 0.85, and 0.76 ppm, respectively. Those during February 2020 ranged from 0.48–1.04, 0.32–0.80, and 0.24–0.64 ppm and averaged 0.73, 0.58, and 0.49 ppm, respectively, which were 16.2%, 31.9%, and 35.8% lower than those during February 2017–2019. Based on the data from the three cities, during February 2020, the average CO decreased by 27.9% compared with that in February 2017–2019.

As shown in Fig. 2(D)(c), in Wuhan, Jingmen, and Enshi, during March 2017–2019, the CO concentrations ranged between 0.48 and 1.60, 0.40 and 1.12, and 0.32 and 1.12 ppm, and averaged 0.82, 0.72, and 0.64 ppm, respectively. Those during March 2020 ranged from 0.48–1.12, 0.24–0.96, and 0.24–0.72 ppm and averaged 0.76, 0.56, and 0.44 ppm, respectively, which were 7.4%, 22.4%, and 31.1% lower than those during March 2017–2019. Based on the data from the three cities, during March 2020, the average CO decreased by 20.3% compared with that in March 2017–2019.

In the first three months of 2020, the CO concentration also showed a significant decrease compared with the same period in the previous three years. This shows that the Lunar New Year holiday and the implementation of epidemic prevention and control actions greatly reduced both the burning of industrial fossil fuels and the traffic flow, thus reducing CO emissions.

Nitrogen dioxide (NO_2) is an important pollutant and oxidant in the atmosphere, mainly derived from high-temperature combustion of fossil fuels, thermal power generation, industrial emissions, and automobile exhaust (Burnett *et al.*, 2004; Jaeglé *et al.*, 2005). Ambient NO_2 is associated with a variety of health hazards. High concentrations of NO_2 can lead to the formation of acid rain and nitrate aerosols, and are also important precursors for O_3 production (Biswas *et al.*, 2019).

As shown in Fig. 2(E)(a), in Wuhan, Jingmen, and Enshi, during January 2017–2019, the NO_2 concentrations ranged between 8.28 and 48.7, 6.82 and 54.1, and 6.33 and 35.1 ppb, and averaged 25.7, 22.9, and 15.2 ppb, respectively. Those during January 2020 ranged from 4.87–37.0, 4.87–30.2, and 2.92–17.0 ppb and averaged 17.9, 14.1, and 9.39 ppb, respectively, which were 30.3%, 38.5%, and 38.1% lower than those during January 2017–2019. Based on the data from the three cities, during January 2020, the average NO_2 decreased by 35.6% compared with that in January 2017–2019.

As shown in Fig. 2(E)(b), in Wuhan, Jingmen, and Enshi, during February 2017–2019, the NO_2 concentrations ranged between 6.33 and 50.2, 6.34 and 35.1, and 4.87 and 21.4 ppb, and averaged 30.0, 16.8, and 10.6 ppb, respectively. Those during the epidemic prevention and control action period (February 2020) ranged from 4.87–17.5, 2.92–12.7, and 1.46–6.82 ppb, with averages of 10.41, 6.01, and 3.68 ppb, respectively, which were 54.7%, 64.3%, and 65.2% lower than that of during February 2017–2019. Based on the data from the three cities, during February 2020, average NO_2 decreased by 61.4% compared with that in February 2017–2019.

As shown in Fig. 2(E)(c), in Wuhan, Jingmen, and Enshi, during March 2017–2019, the NO_2 concentrations ranged between 11.2 and 43.3, 6.33 and 35.1, and 4.87 and 21.4 ppb

and averaged 26.6, 17.8, and 13.1 ppb, respectively. Those during March ranged from 6.82–15.6, 3.90–11.7, and 2.92–13.6 ppb, with averages of 10.5, 6.60, and 7.05 ppb, respectively, which were 60.6%, 63.0%, and 46.2% lower than those during March 2017–2019. Based on the data from the three cities, during March 2020, average NO_2 decreased by 56.6% compared with that in March 2017–2019.

From January to March 2020, the decrease in NO_2 concentration is of great significance, and the reduction rate is much higher than other pollutants. Especially in February and March when the epidemic prevention and control actions were taken, the NO_2 concentration decreased by more than 60% compared with the same period in 2019–2019. This may have been because during the epidemic prevention and control actions, industrial production activities and transportation were greatly restricted, resulting in a sharp reduction in the emission of NO_2 from both industrial production and vehicle exhaust.

Ozone (O_3) is an important gas in the process of atmospheric chemical reactions and is also one of the key greenhouse gases. Due to the rapid development that has occurred in the past few decades, power plant emissions, industrial exhaust gas, and the burning of fossil fuels have indirectly caused increased ambient O_3 pollution (Logan *et al.*, 1981; Ryerson *et al.*, 2001). Solar radiation and higher air humidity, as well as increased NO_x and VOCs (volatile organic compounds) in the environment, promote the photochemical reaction that produces O_3.

It is worth noting that the pattern of O_3 concentration was completely opposite to the pattern of the other five air pollutants. As shown in Fig. 2(F)(a), in Wuhan, Jingmen, and Enshi, during January 2017–2019, the O_3 concentrations ranged between 2.80 and 42.0, 6.53 and 49.9, and 1.87 and 34.5 ppb and averaged 20.4, 26.8, and 14.2 ppb, respectively. Those during January 2020 ranged from 2.33–51.3, 9.80–61.1, and 2.80–30.8 ppb and averaged 22.3, 31.0, and 16.1 ppb, respectively, which was an increase of 9.6%, 15.5%, and 13.1% compared with that of during January 2017–2019. Based on the data from the three cities, during January 2020, the average O_3 rose by 12.7% compared with that in January 2017–2019.

As shown in Fig. 2(F)(b), in Wuhan, Jingmen, and Enshi, during February 2017–2019, the O_3 concentrations ranged between 9.33 and 57.9, 11.7 and 62.5, and 1.87 and 47.6 ppb and averaged 27.7, 36.3, and 21.0 ppb, respectively. Those during February 2020 ranged from 18.2–49.5, 19.1–54.1, and 8.40–33.6 ppb, and averaged 35.2, 39.5, and 22.4 ppb, respectively, which was an increase of 27.1%, 8.9%, and 6.9% compared with that of during February 2017–2019. Based on the data from the three cities, during February 2020, the average O_3 rose by 14.3% compared with that in February 2017–2019.

As shown in Fig. 2(F)(c), in Wuhan, Jingmen, and Enshi, during March 2017–2019, the O_3 concentrations ranged between 5.13 and 65.8, 19.1 and 72.3, and 2.33 and 48.1 ppb and averaged 36.2, 44.6, and 28.2 ppb, respectively. Those during March 2020 ranged from 24.7–63.5, 22.4–72.3, and 14.0–51.3 ppb, and averaged 42.1, 44.6, and 28.2 ppb, respectively, which was an increase of 16.3%, 3.2%, and

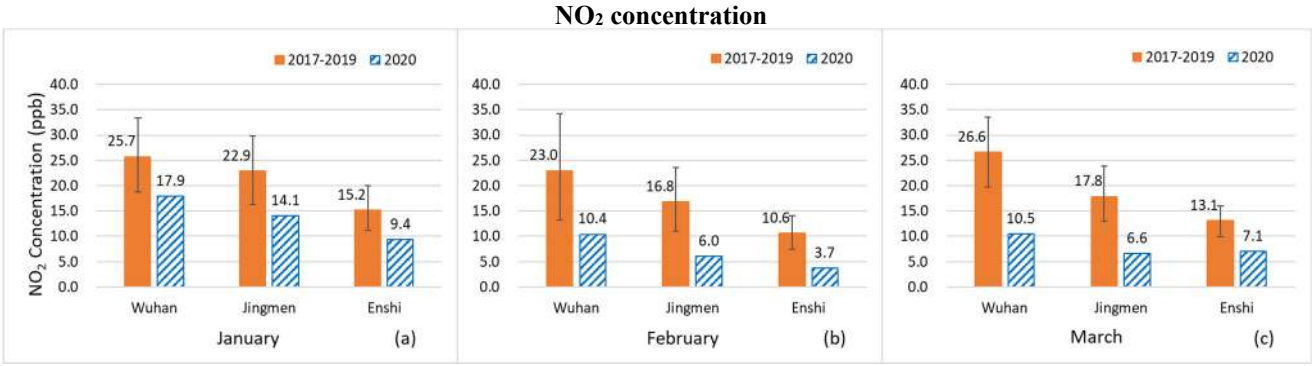

Fig. 2(E). The average concentrations of NO_2 in January, February, and March 2017–2019 and those of 2020, respectively.

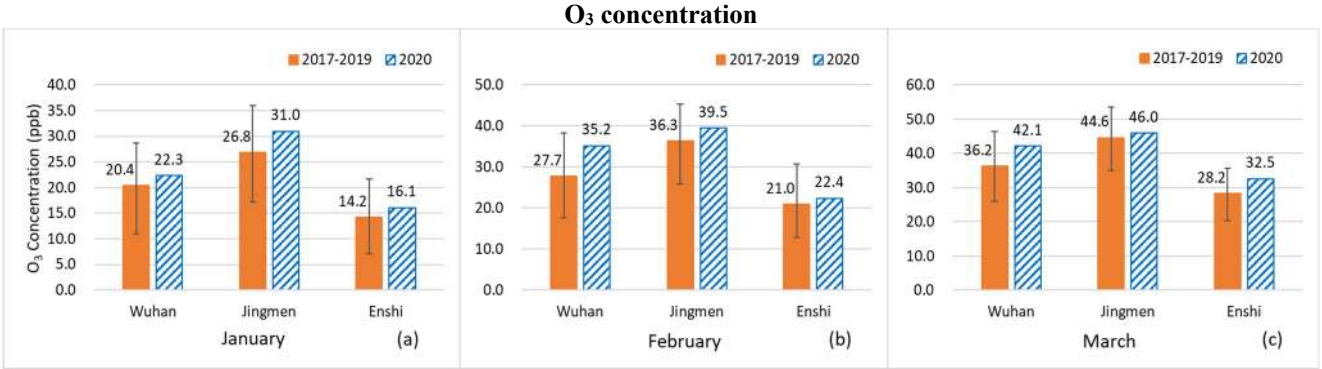

Fig. 2(F). The average concentrations of O_3 in January, February and March 2017–2019 and those of 2020, respectively.

15.4% compared with that of during March 2017–2019. Based on the data from the three cities, during February 2020, the average O_3 rose by 11.6% compared with that in February 2017–2019.

It can be seen that from January to March 2020, the average concentration of O_3 was significantly higher than the average concentration in the same period in the previous three years (2017–2019), which may have been caused by a lower level of NO_x in 2020. According to previous studies, the level of O_3 is closely related to NO_2 and VOCs. When the NO_x concentration is low, NO_x promotes the formation of O_3, and the concentration of VOCs has little effect on O_3. When the VOC concentration is low, NO_x concentration is negatively correlated with O_3 production (Chameides *et al.*, 1992). It can be seen that from January to March 2020, the O_3 concentration and the NO_2 concentration in the three cities are inversely proportional.

Under sufficient intensity of solar radiation, NO_2 acts as a precursor in photochemical reactions and is first dissociated into NO and O (^{3}P):

$$NO_2 + hv\ (\lambda \leq 430\ nm) \rightarrow NO + O(^3P)$$
$$O(^3P) + O_2 \rightarrow O_3$$
$$NO + O_3 \rightarrow NO_2 + O_2$$

It can be seen that NOx is one of the important precursors for O_3 production, and NO is the direct cause of O_3 depletion. Lower levels of NO_2 in the atmosphere will cause a reduction in NO, which reduces the possibility of NO reacting with O_3, resulting in the accumulation of O_3. In general, urban NO_x and O_3 have negative correlation characteristics, which is particularly obvious in colder winter. This is because in the summer, due to the intense solar radiation and the dominant photochemical reactions that occur at this time, the environment is more suitable for the accumulation of O_3. In winter, the photochemical reaction during the day is relatively weak, so a higher NO_2 concentration within a specific range is beneficial to the consumption of O_3, but a lower NO_2 concentration causes more O_3 to be generated during the day that cannot be further effectively converted (Zhao *et al.*, 2018a; Biswas *et al.*, 2019). This is a good explanation for the significant increase in O_3 concentration in the three cities in February and March when the epidemic prevention and control actions were taken.

AQI Distribution

In order to investigate the impact of the COVID-19 outbreak on the Air Quality Index (AQI) in central China, the AQI distribution for Wuhan, Jingmen, and Enshi in January, February and March 2017–2019 and those of 2020 are shown in Fig. 3.

As shown in Fig. 3, during January 2017–2019, the average AQIs in Wuhan, Jingmen, and Enshi ranged from 45–232, 53–348, and 33–298 and averaged 119.3, 150.9, and 102.3, respectively, while those during January 2020 ranged between 40–142, 38–195, and 23–94 and averaged 83.5, 116.7, and 52.5, respectively, which were 30.1%, 22.7%, and 48.6%, lower than those in January 2017–2019, respectively. In February 2017–2019, the average AQIs in Wuhan, Jingmen, and Enshi ranged from 28–219, 52–229, and 25–152 and averaged 93.8, 112.5, and 71.5, respectively, while those during February 2020 ranged between 20–128, 36–185, and 23–122 and averaged 57.2, 81.3, and 62.4, respectively, which were 39.0%, 27.8%, and 12.8%, lower than those during February 2017–2019, respectively. In March 2017–2019, the average AQIs in Wuhan, Jingmen, and Enshi ranged from 33–272, 40–137, and 23–94 and averaged 80.5, 78.1, and 54.4, respectively, while those during March 2020 ranged from 28–80, 37–110, and 29–125 and averaged 55.5, 70.1, and 55.8, respectively. Those in Wuhan and Jingmen were 31.1% and 10.3% lower than those of during March 2017–2019, respectively, but that of Enshi increased by 2.6% compared with that during March 2017–2019.

Based on the results for the three cities under observation, in January 2017–2019, the average AQIs ranged from 33–348 and averaged 124.2, while those during January 2020 ranged between 23–195 and averaged 84.2, which was 32.2% lower than that in January 2017–2019. In February 2017–2019, the average AQIs ranged from 25–229 and averaged 92.6, while those during February 2020 ranged from 20–185 and averaged 66.9, which was 27.7% lower than that in February 2017–2019. However, in March 2017–2019, the average AQIs in the three cities ranged between 23 and 272 and averaged 71.0, while those during March 2020 ranged between 28 and 125 and averaged 60.4, which was 14.9% lower than that in March 2017–2019.

It can be seen that the air quality during January–March 2020 was significantly improved compared with the same period in 2017–2019. The improvement in air quality in January 2020 can be attributed to the reduction in industrial production and construction activities during the Lunar New Year holidays. The reduction in February and March 2020 can be attributed to the strict implementation of epidemic prevention and control actions, which has resulted in a substantial reduction in transportation and industrial emissions. In March, as the atmospheric temperature increased, the vertical dilution and dispersion of air pollutants were accelerated, and the air quality significantly improved, so the impact of epidemic prevention and control actions on air quality weakened.

Distribution of Six AQI Classes

This study also made a statistical analysis for the distribution of six AQI classes in the three cities in January, February, and March 2017–2019 and those in 2020, respectively.

It can be seen from Fig. 4(A)(a), in Wuhan, in January 2017–2019, the proportions of classes I, II, III, IV, V, and VI were 3.2%, 37.6%, 36.6%, 16.1%, 6.5%, and 0%, respectively. While during January 2020, the proportions of AQI classes I, II, III, IV, V, and VI were 16.1%, 51.6%, 32.3%, 0%, 0%, and 0%, respectively. It can be seen that during January 2020, the combined proportions of Class I and Class II increased from 40.8% to 67.7%, while the combined proportions of classes IV, V, and VI decreased from 22.6% to zero, which indicates that the air quality had greatly improved.

In Jingmen (Fig. 4(A)(a)), in January 2017–2019, the proportions of AQI classes I, II, III, IV, V, and VI were 0%,

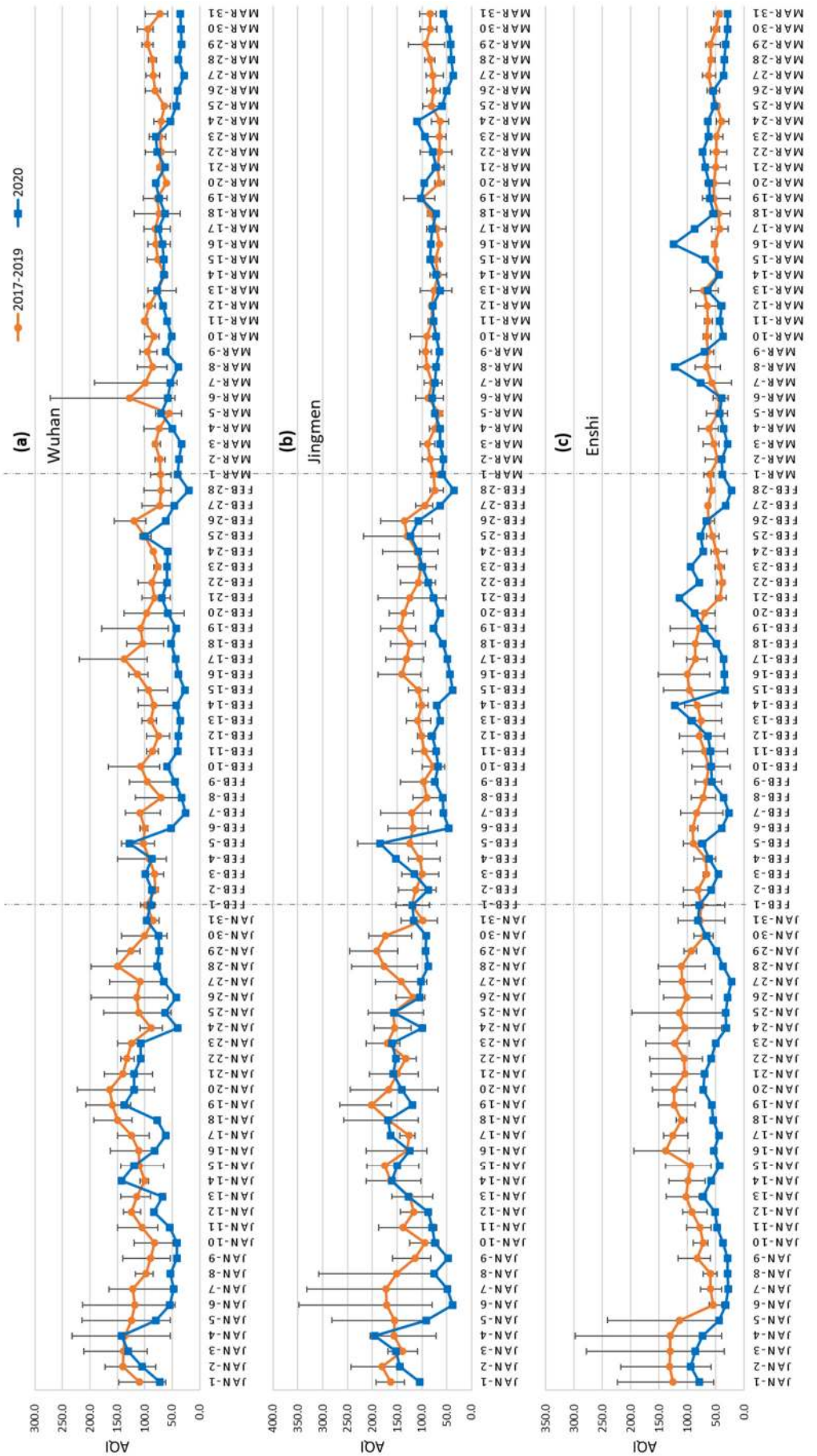

Fig. 3. Daily AQIs in January, February and March 2017–2019 and those of 2020, respectively.

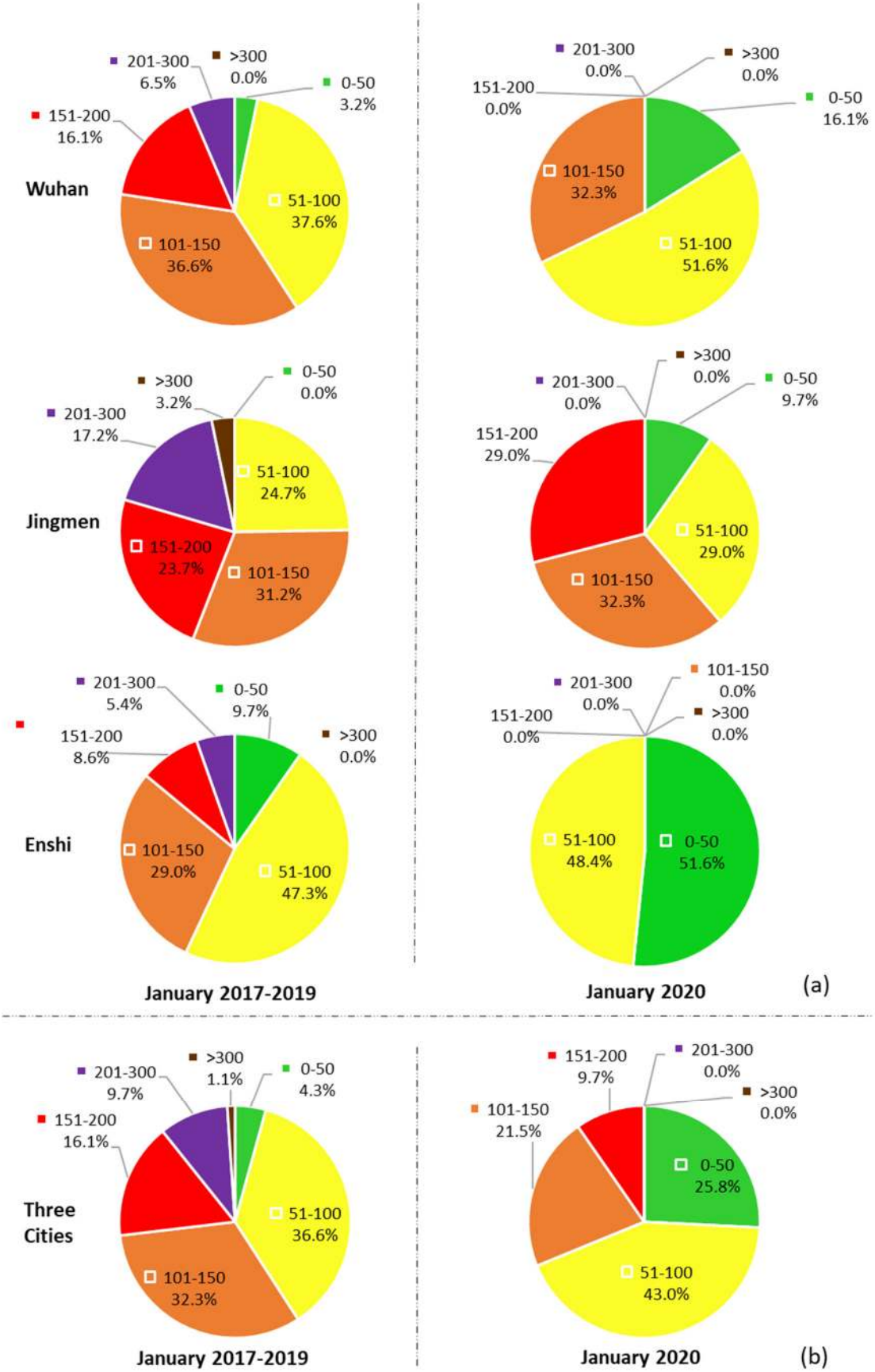

Fig. 4(A). The distribution of six AQI classes (a) for Wuhan, Jingmen, and Enshi in January 2017–2019 and January 2020, respectively and (b) for the three cities under observation.

24.7%, 31.2%, 23.7%, 17.2%, and 3.2%, respectively. However, in January of 2020, those of the same AQI classes were 9.7%, 29.0%, 32.3%, 29.0%, 0%, and 0%, respectively. The combined proportions of classes I and II increased from 24.7% to 38.7%, and the combined proportion of classes IV, V, and VI decreased from 44.1% to 29.0%.

For Enshi (Fig. 4(A)(a)), which had the greatest improvement in air quality, in January 2017–2019, the proportions of classes I, II, III, IV, V, and VI were 9.7%, 47.3%, 29.0%, 8.6%, 5.4%, and 0%, respectively. In January 2020, the same AQI class proportions were 51.6%, 48.4%, 0%, 0%, 0%, and 0%. The combined proportion of Class I and Class II increased from 57.0% to 100%, respectively, while the combined proportions of classes III, VI, V, and VI decreased from 43.0% to zero. It can be seen that the air quality of the three cities in January 2020 improved very significantly compared with the same period in the previous three years.

Fig.4 (A)(b) shows the distribution of AQI classes for the three-city combination in January 2017–2019 and in January 2020, respectively. It can be seen that from 2017 to 2019, the AQI class distribution for classes I, II, III, IV, V, and VI in the three cities was 4.3%, 36.6%, 32.3%, 16.1%, 9.7%, and 1.1%, respectively, but in January 2020, it was 25.8%, 43.0%, 21.5%, 9.7%, 0%, and 0%, respectively. The combined proportion of classes I and II increased from 40.9% to 68.8%, while that of classes VI, V, and VI decreased from 26.9% to 9.7%, respectively. At the same time, classes V and VI did not appear in the three cities. Based on the data from the three cities, it can be seen that the air quality in Hubei Province in January 2020 improved from the same period in the previous three years. This may have been due to the production stagnation caused by the Chinese New Year holiday in late January and the closure of factories caused by the COVID-19 epidemic prevention and control actions.

As shown in Fig. 4(B)(a), in Wuhan, in February 2017–2019, the proportions of classes I, II, III, IV, V, and VI were 6.1%, 56.1%, 32.9%, 3.7%, 1.2%, and 0%, respectively. In February 2020 when comprehensive epidemic prevention and control actions were taken, the proportions of classes I, II, III, IV, V, and VI were 46.4%, 50.0%, 3.6%, 0%, 0%, and 0%, respectively. This indicated that during the epidemic control period, the combined proportion of Class I and Class II increased from 62.2% to 96.4 %, while the combined proportion of classes IV, V, and VI decreased from 4.9% to zero, which indicates that the air quality improved significantly.

In Jingmen (Fig. 4(B)(a)), in February 2017–2019, the AQI proportions of classes I, II, III, IV, V, and VI were 0%, 45.1%, 39.0%, 13.4%, 2.4%, and 0%, respectively. However, in February of 2020, those of AQI proportions were 17.9%, 57.1%, 17.9%, 7.1%, 0%, and 0%, respectively. The combined proportions of classes I and II increased from 45.1% to 75.0%, while the combined proportion of classes IV, V, and VI decreased from 15.8% to 7.1%, which indicates that there was a significant improvement in air quality.

For Enshi (Fig. 4(B)(a)), in February 2017–2019, the AQI proportions of classes I, II, III, IV, V, and VI were 25.0%, 57.1%, 16.7%, 1.2%, 0%, and 0%, respectively. In February 2020, the AQI proportions were 35.7%, 51.1%, 7.1%, 0%, 0%, and 0%. This was similar to both Wuhan and Jingzhou. However, in Enshi, the combined proportion of classes I and II increased from 82.1% to 86.8%, while the combined proportion of classes IV, V, and VI decreased from 1.2% to zero. Even though the improvement in air quality was not a big step, it is very clear that the epidemic prevention and control action had a good effect on air quality.

Fig. 4(B)(b) shows the distribution of AQIs for three-city combination in February 2017–2019 and in February 2020, respectively. It can be seen that from 2017 to 2019, the AQI distribution of classes I, II, III, IV, V, and VI in the three cities was 10.5%, 52.8%, 29.4%, 6.0%, 1.2%, and 0%, respectively, but in February 2020, the distribution was 33.3%, 54.8%, 9.5%, 2.4%, 0%, and 0%, respectively. The combined proportion of classes I and II increased from 63.3% to 88.1%, while the combined proportion of classes IV, V, and VI decreased from 7.2% to 2.4%. According to the data for the three cities, it is clear that in February 2020, the air quality of the three cities improved significantly compared with that in February 2017–2019 (non-epidemic period). This is because in February 2020, Hubei Province implemented strict epidemic prevention and control actions including quarantines, industrial plant closures, and traffic restrictions that greatly reduced air pollutant emissions.

It can be seen in Fig. 4(C)(a), that in Wuhan, in March 2017–2019, the AQI proportions of classes I, II, III, IV, V, and VI were 8.6%, 77.4%, 11.8%, 1.1%, 1.1%, and 0%, respectively. During March 2020 when comprehensive epidemic prevention and control action were taken, the AQI proportions of classes I, II, III, IV, V, and VI were 38.7%, 61.3%, 0%, 0%, 0%, and 0%, respectively. This indicated that during the epidemic control period, the combined proportion of Class I and Class II increased from 86.0% to 100%, which revealed that the air quality had greatly improved.

In Jingmen, in March 2017–2019, the AQI proportions of classes I, II, III, IV, V and VI were 5.4%, 82.8%, 11.8%, 0%, 0%, and 0%, respectively. However, in March of 2020, they were 16.1%, 77.4%, 6.5%, 0%, 0%, and 0%. The combined AQI proportions of classes I and II increased from 88.2% to 93.5%, while the combined proportion of classes IV, V, and VI was zero.

For Enshi, in March 2017–2019, the AQI proportions of classes I, II, III, IV, V, and VI were 40.9%, 59.1%, 0%, 0%, 0%, and 0%, respectively. In March 2020, the AQI proportions were 48.4%, 45.2%, 6.5%, 0%, 0%, and 0%. This indicated that Enshi had good air quality in March 2017–2020. The forest coverage in Enshi accounts for about 70% of the area, so after the temperature rose in March, the vertical convention and dispersion of air pollutants was further increased, and the air quality was improved, so the control actions of the epidemic did not display a significant impact.

Fig. 4(C)(b) shows the distribution of AQI Class for the three-city combination in March 2017–2019 and in March 2020, respectively. It can be seen that from 2017 to 2019, the AQI distribution of classes I, II, III, IV, V, and VI in the three cities was 18.3%, 73.1%, 7.9%, 0.4%, 0.4%, and 0%, respectively, but in March 2020, it was 34.4%, 61.3%, 4.3%, 0%, 0%, and 0%, respectively. The combined proportions of classes I and II increased from 91.4% to 95.7%, while the

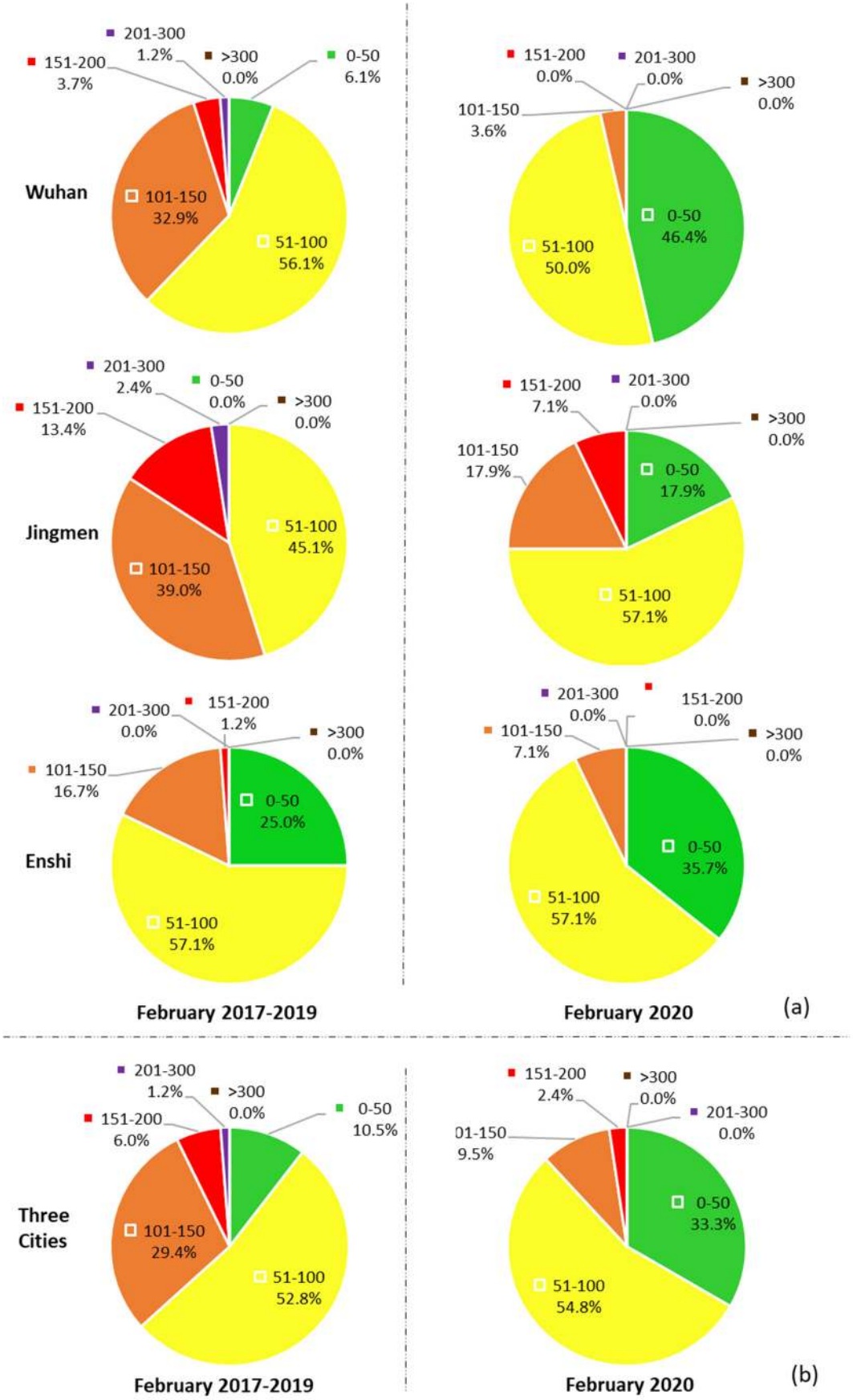

Fig. 4(B). The distribution of six AQI classes (a) for Wuhan, Jingmen, and Enshi in February 2017–2019 and February 2020, respectively and (b) for the three cities under observation.

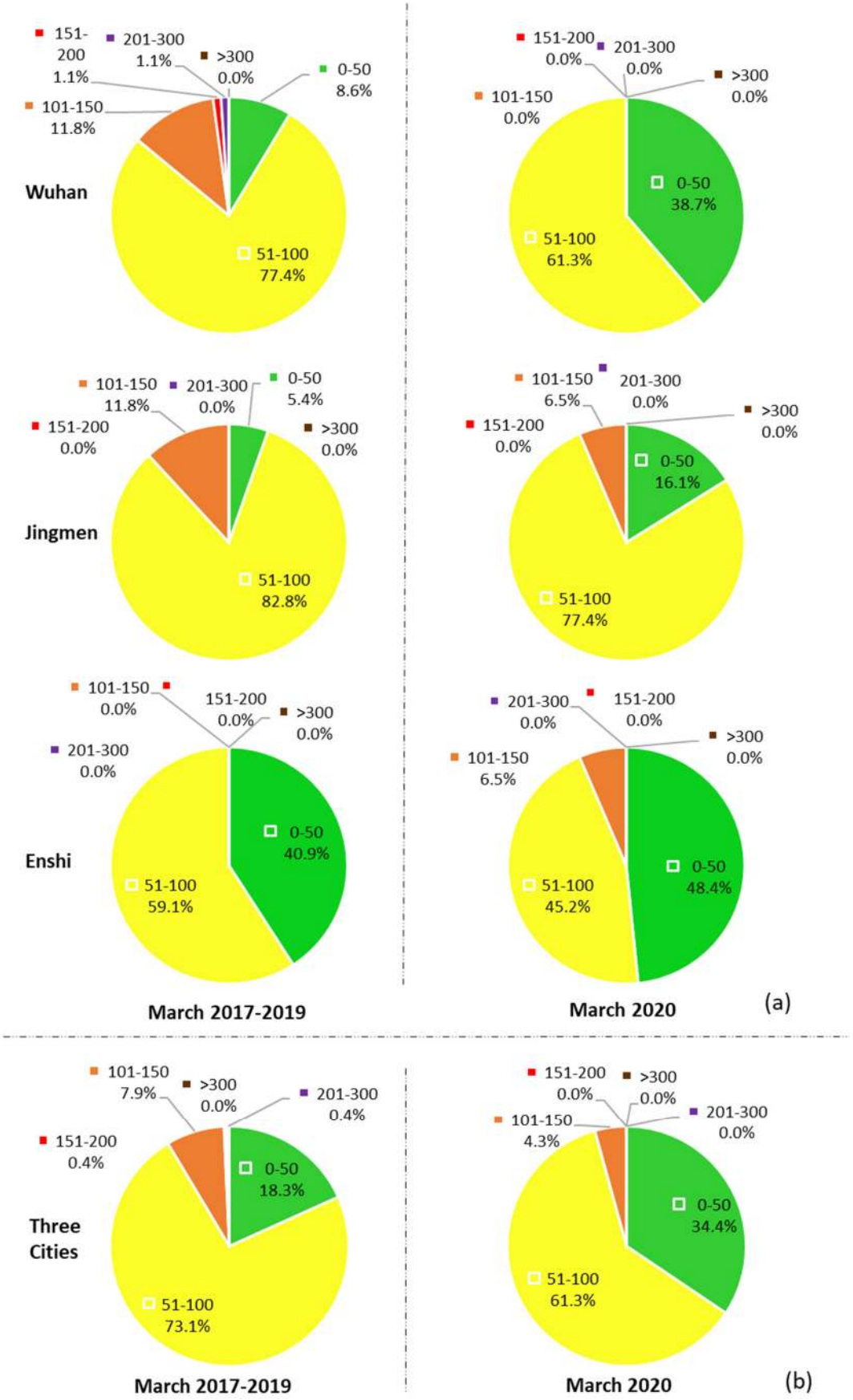

Fig. 4(C). The distribution of six AQI classes (a) for Wuhan, Jingmen, and Enshi in March 2017–2019 and March 2020, respectively and (b) for the three cities under observation.

combined proportion of classes IV, V, and VI decreased from 0.8% to zero. Due to the strict epidemic prevention and control actions, the air quality in Hubei Province in March 2020 improved.

Indicatory Air Pollutants

The indicatory air pollutants for the different AQI classes from January to March 2017–2019 and that of 2020, respectively are shown in Table 1.

Combined with the data for the three cities, in January 2017–2019, the indicatory air pollutants for the AQIs were predominant in the following order: $PM_{2.5}$ (92.0%), PM_{10} (4.3%), and NO_2 (3.6%), and those of each AQI were Class I: $PM_{2.5}$ (3.2%) (followed by NO_2 (0.7%) and PM_{10} (0.4%)), Class II: $PM_{2.5}$ (30.1%) (followed by PM_{10} (2.9%) and NO_2 (2.5%)), Class III: $PM_{2.5}$ (32.3%), Class IV: $PM_{2.5}$ (15.7%) (followed by NO_2 (0.4%)), Class V: $PM_{2.5}$ (9.7%), and Class VI: $PM_{2.5}$ (1.1%), respectively. In January 2020, the order was $PM_{2.5}$ (87.0%), NO_2 (6.5%), O_3 (3.2%), and PM_{10} (3.2%), and the indicatory air pollutants for each AQI were Class I: $PM_{2.5}$ (15.1%) (followed by NO_2 (4.3%), PM_{10} (3.2%), and O_3 (3.2%)), Class II: $PM_{2.5}$ (40.8%) (followed by NO_2 (2.2%)), Class III: $PM_{2.5}$ (21.5%), and Class IV: $PM_{2.5}$ (9.7%), respectively, while both Class V and Class VI were not present. It can be seen that in January 2020, the proportion of days with NO_2 and O_3 as indicatory air pollutants was slightly increased from 3.6% to 9.7%, while the proportion of days with $PM_{2.5}$ and PM_{10} as indicatory air pollutants decreased from 96.3% to 90.2% compared with that in January 2017–2019.

The combined data for the three cities in February 2017–2019 show that the indicatory air pollutants for the AQIs were in the following order: $PM_{2.5}$ (74.8%), PM_{10} (16.5%), NO_2 (7.3%), O_3 (1.2%), and CO (0.4%), and those of each AQI were Class I: $PM_{2.5}$ (4.8%) (followed by PM_{10} (4.4%), O_3 (0.8%), and CO (0.4%)), Class II: $PM_{2.5}$ (36.4%) (followed by PM_{10} (10.9%), NO_2 (5.2%), and O_3 (0.4%)), Class III: $PM_{2.5}$ (26.2%) (followed by NO_2 (2.0%) and PM_{10} (1.2%)), Class IV: $PM_{2.5}$ (6.1%), and Class V: $PM_{2.5}$ (1.2%), respectively, and Class VI did not occur. In February 2020, during the epidemic prevention and control period, the order was $PM_{2.5}$ (80.6%), O_3 (17.2%), PM_{10} (1.1%), and CO (1.1%), and the indicatory air pollutants for each AQI were Class I: $PM_{2.5}$ (18.4%) (followed by O_3 (14.9%) and CO (1.1%)), Class II: $PM_{2.5}$ (50.7%) (followed by O_3 (2.3%) and PM_{10} (1.1%)), Class III: $PM_{2.5}$ (9.2%), and Class IV: $PM_{2.5}$ (2.3%), respectively, while classes V and VI did not occur. It can be seen that in February 2020, the proportion of days in which O_3 was as an indicatory air pollutant in classes I and II increased significantly (from 1.2% to 17.2%). In February 2020, the proportion of PM_{10} and NO_2 as indicator air pollutants decreased (from 16.5% to 1.1%, and from 7.3% to 0%, respectively) compared with that in February 2017–2019. This shows that during the epidemic control period, restrictions on transportation and industrial production caused significant reductions in air pollutant emissions.

The combined results for the three cities in March 2017–2019 show that the indicatory air pollutants for the AQIs were in the following order $PM_{2.5}$ (45.4%), PM_{10} (33.0%),

Table 1. Indicatory air pollutants and their cumulative daily proportions for the three cities in January, February, and March 2017–2019 and that of 2020, respectively.

Year	AQI	January						February						March					
		$PM_{2.5}$	PM_{10}	SO_2	CO	NO_2	O_3	$PM_{2.5}$	PM_{10}	SO_2	CO	NO_2	O_3	$PM_{2.5}$	PM_{10}	SO_2	CO	NO_2	O_3
2017–2019	0–50	3.2%	0.4%	0.0%	0.0%	0.7%	0.0%	4.8%	4.4%	0.0%	0.4%	0.0%	0.8%	3.5%	9.0%	0.0%	0.4%	1.4%	3.9%
	51–100	30.1%	3.9%	0.0%	0.0%	2.5%	0.0%	36.4%	10.9%	0.0%	0.0%	5.2%	0.4%	35.1%	24.0%	0.0%	0.0%	10.4%	3.6%
	101–150	32.3%	0.0%	0.0%	0.0%	0.0%	0.0%	26.2%	1.2%	0.0%	0.0%	2.0%	0.0%	6.1%	0.0%	0.0%	0.0%	1.8%	0.0%
	151–200	15.7%	0.0%	0.0%	0.0%	0.4%	0.0%	6.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
	201–300	9.7%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
	> 300	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2020	0–50	15.1%	3.2%	0.0%	0.0%	4.3%	3.2%	18.4%	0.0%	0.0%	1.1%	0.0%	14.9%	8.6%	6.5%	0.0%	0.0%	2.2%	17.2%
	51–100	40.8%	0.0%	0.0%	0.0%	2.2%	0.0%	50.7%	1.1%	0.0%	0.0%	0.0%	2.3%	36.5%	12.9%	0.0%	0.0%	0.0%	11.8%
	101–150	21.5%	0.0%	0.0%	0.0%	0.0%	0.0%	9.2%	0.0%	0.0%	0.0%	0.0%	0.0%	3.2%	1.1%	0.0%	0.0%	0.0%	0.0%
	151–200	9.7%	0.0%	0.0%	0.0%	0.0%	0.0%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	201–300	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	> 300	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

NO_2 (13.6%), O_3 (7.5%), and CO (0.4%), and those of each AQI were Class I: PM_{10} (9.0%) (followed by O_3 (3.9%), $PM_{2.5}$ (3.5%), NO_2 (1.4%), and CO (0.4%)), Class II: $PM_{2.5}$ (35.1%) (followed by PM_{10} (24.0%), NO_2(10.4%), and O_3 (3.6%)), Class III: $PM_{2.5}$(6.1%) (followed by NO_2 (1.8%)), and Class IV: $PM_{2.5}$ (0.4%), respectively, Class VI did not occur. In March 2020, they were in the following order: $PM_{2.5}$ (48.3%), O_3 (29.0%), PM_{10} (20.4%), and NO_2 (2.2%), and the order of the indicatory air pollutants for each AQI were Class I: O_3 (17.2%) (followed by $PM_{2.5}$(8.6%), PM_{10} (6.5%), and NO_2(2.2%)), Class II: $PM_{2.5}$ (36.5%) (followed by PM_{10} (12.9%), and O_3 (11.8%)), and Class III: $PM_{2.5}$ (3.2%) (followed by PM_{10} (1.1%)), respectively, while classes IV, V, and VI did not occur. Consistent with the trend in February, in March 2020, the proportion of days with O_3 as an indicatory air pollutant increased significantly (from 7.5% to 29.0%), while the proportion of PM_{10} and NO_2 as indicatory air pollutants decreased (from 33.0% to 20.4% and from 13.6% to 2.2%, respectively).

To summarize, in January to March 2017–2019 in the three cities, the indicatory air pollutants for the AQIs occurred in the following order: $PM_{2.5}$ (70.7%), PM_{10} (17.9%), NO_2 (8.2%), O_3 (2.9%), and CO (0.3%), while those in the same period in 2020 were in the following order: $PM_{2.5}$ (72.0%), O_3 (16.5%), PM_{10} (8.3%), NO_2 (2.9%), and CO (0.4%). This indicated that from January–March 2020, the proportion of days with O_3 as an indicatory air pollutant increased significantly (from 2.9% to 16.5%), while the proportion of PM_{10} and NO_2 as indicatory air pollutants decreased (from 17.9% to 8.3% and from 8.2% to 2.9%, respectively) significantly. It can be seen that from January to March 2020, $PM_{2.5}$ was still a major indicatory air pollutant. However, due to strict epidemic prevention and control actions, vehicle exhaust and industrial production emissions were significantly reduced, which caused the concentration of NO_2 and PM_{10} to be decreased. The reason for the obvious increase in the proportion of days of O_3 as an indicatory air pollutant may be that as the temperature increases, the photochemical reaction to generate O_3 intensifies, but a lower level of NO_2 cannot effectively convert O_3, which leads to an increase in O_3 levels.

CONCLUSIONS

1. The Lunar New Year holiday in late January 2020 and the COVID-19 epidemic prevention and control actions in February and March 2020 had a significant impact on the air quality of the three cities under observation. In January 2020, the average concentrations of atmospheric $PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2 in the three cities (combination of Wuhan, Jingmen, and Enshi) were 61.4 μg m^{-3}, 64.8 μg m^{-3}, 2.39 ppb, 0.73 ppm, and 13.8 ppb, and were 36.2%, 37.6%, 45.0%, 28.8%, and 35.6% lower than those of January 2017–2019, respectively. During February 2020, when the epidemic prevention and control actions were taken, the average concentrations of atmospheric $PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2 in three cities were 46.1 μg m^{-3}, 50.8 μg m^{-3}, 2.56 ppb, 0.60 ppm, and 6.70 ppb, and were 30.1%, 40.5%, 33.4%, 27.9%, and 61.4% lower than those of February 2017–2019, respectively. As for March 2020, these concentrations were 38.2 μg m^{-3}, 57.2 μg m^{-3}, 2.81 ppb, 0.59 ppm, and 8.04 ppb, and were 15.8%, 22.5%, 29.7%, 20.3%, and 56.6% lower than those of March 2017–2019, respectively.
2. It is worth noting that the pattern of O_3 concentration was completely opposite to the pattern of the other five air pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2). The average concentrations of atmospheric O_3 in three cities in January, February and March 2017–2019 were 20.5, 28.2, and 36.3 ppb, respectively, while those in 2020 were 23.1, 32.4, and 38.3 ppb, respectively, which were 12.7%, 14.3%, and 11.6% higher than those of 2017–2019, respectively. This is because a lower concentration of NO_2 hindered the NO + O_3 reaction, so O_3 was could not be effectively depleted further.
3. Based on the results for the three cities, in January, February, and March 2017–2019, the AQIs averaged 124.2, 92.6, and 71.0 respectively, while those during 2020 averaged 84.2, 66.9, and 60.4, respectively, and were 32.2%, 27.7%, and 14.9% lower than that in 2017–2019. The improvement in air quality in January 2020 can be attributed to the reduction in industrial production and construction activities during the Lunar New Year holidays. The reduction in February and March 2020 can be attributed to the strict implementation of epidemic prevention and control actions, which resulted in a substantial reduction in transportation and industrial emissions.
4. Based on the combination of the three cities, the combined proportion of AQI Classes I and Class II in January, February and March 2020, increased by 27.9%, 24.8%, and 4.3%, respectively, while the combined proportion of AQI classes IV, V, and VI was reduced by 17.2%, 4.8%, and 0.8% respectively. It is clear that from January–March 2020, the air quality of the three cities improved significantly compared with that in 2017–2019.
5. As to the indicatory air pollutants for the different AQI Classes in three cities, the results indicated that during January–March 2020, the proportion of days with O_3 as an indicatory air pollutant, increased (from 2.9% to 16.5%), while the proportions of PM_{10} and NO_2 decreased (from 17.9% to 8.3% and from 8.2% to 2.9%, respectively). During January–March 2020, $PM_{2.5}$ was still a major indicatory air pollutant. However, due to strict epidemic prevention and control actions, the emissions from vehicle exhaust and industrial production were significantly reduced, which caused the concentration of NO_2 and PM_{10} to be decreased. The reason for the obvious increase in the proportion of days with O_3 as an indicatory air pollutant may be that as the temperature increased, the photochemical reaction to generate O_3 intensified, but a lower level of NO_2 and NO made it impossible to effectively convert O_3, which led to an increase in O_3 levels.

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