



Temporal Variations in the Air Quality Index and the Impact of the COVID-19 Event on Air Quality in Western China

Jiajia Zhang¹, Kangping Cui^{1*}, Ya-Fen Wang^{2*}, Jhong-Lin Wu^{3,4}, Wei-Syun Huang⁵, Shun Wan¹, Kaijie Xu¹

¹ School of Resources and Environmental Engineering, Hefei University of Technology, Hefei 230009, China

² Department of Environmental Engineering, Chung-Yuan Christian University, Taoyuan 32023, Taiwan

³ Environmental Resource and Management Research Center, National Cheng Kung University, Tainan 70101, Taiwan

⁴ Sustainable Environment Research Laboratories, National Cheng Kung University, Tainan 70101, Taiwan

⁵ Department of Atmospheric Sciences, National Central University, Taoyuan 32001, Taiwan

ABSTRACT

This study investigated the AQI (air quality index) and atmospheric pollutants including PM_{2.5}, PM₁₀, CO, SO₂, NO₂ and O₃ in Chongqing, Luzhou and Chengdu from 2017 to 2019. In addition, the impacts of the COVID-19 event on the air quality in the three cities in 2020 were compared and discussed. For the combined AQIs for the three cities, in spring, the daily AQIs ranged between 25 and 182 and averaged 72.1. In summer, the daily AQIs ranged between 24 and 206 and averaged 77.5. In autumn, the daily AQIs ranged between 22 and 170 and averaged 61.1, and in winter, the daily AQIs ranged between 28 and 375 and averaged 99.6. The distributions of the six AQI classes in spring were 3%, 94%, 3%, 0%, 0%, and 0%; in summer, they were 11%, 74%, 15%, 0%, 0% and 0%; in autumn, they were 29%, 70%, 1%, 0%, 0%, and 0%, and in winter, they were 1%, 52%, 44%, 3%, 0%, and 0%, respectively. The average AQIs, in order, were Chengdu (85.4) > Chongqing (73.8) > Luzhou (73.2). Both the highest AQIs and PM_{2.5} (as the major indicatory air pollutant) occurred mainly in the low temperature season (January, December, and February), while O₃ was the main air pollutant in June and August when the weather was hot. In February 2020, during the epidemic prevention and control actions taken in response to COVID-19 for the three cities, the combined AQIs for the top five days with the highest AQIs in February 2020 was 79.4, which was 23.6% lower than that from 2017–2019 (AQI = 100.7), and the average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, and NO₂ were 89.4 µg m⁻³, 106 µg m⁻³, 2.31 ppb, 0.72 ppm, and 12.3 ppb, respectively, and were 17.9%, 30.8%, 83.8%, 19.8%, and 62.1%, lower than those in February 2017–2019. However, the average O₃ concentration (31.8 ppb) in February 2020 rather than decreasing, increased by 6.2%. This is because a lower NO₂ concentration hindered the NO + O₃ reaction and led to increase O₃ concentration in the ambient air.

Keywords: COVID-19; AQI; PM_{2.5}; PM₁₀; SO₂; NO_x; CO; O₃.

INTRODUCTION

Over the past few decades, China has developed rapidly in terms of economic growth and urbanization. Automobile exhaust, industrial activities, and biomass combustion have released a significant amount of pollutants into the atmosphere. Air pollution was a serious issue many cities (Liu *et al.*, 2012; Liu and Wang, 2014; Li *et al.*, 2017a).

An estimated 2.5 million people are killed each year by indoor and outdoor air pollution in China (Kulmala, 2015).

Previous research investigated the relationship between air pollutants and human health (Pope and Dochery, 2006; Cao *et al.*, 2012; Heal *et al.*, 2012; Pope and Dochery, 2013; Jin *et al.*, 2017). Studies have shown that inhaling PM_{2.5} can cause pneumonia and that it can dissolve in the bloodstream and cause heart and reproductive system diseases (Yang *et al.*, 2017). PM₁₀ also has a significant impact on the mortality related to cardiovascular diseases and respiratory diseases (Abe *et al.*, 2018). PM_{2.5} is more harmful than PM₁₀ (Deng *et al.*, 2013a, b). SO₂ is a common air pollutant that can cause health damage such as bronchitis and bronchial asthma and thus damage health (Hansell *et al.*, 2011; Cerón-Bretón *et al.*, 2018). CO in the atmosphere not only destroys the nerve function of the heart, but also affects the central nervous system and even leads to death from asphyxia (Yang *et al.*, 2012). NO₂ can hurt the function of the human respiratory

* Corresponding author.

E-mail address: cui kangping@163.com (K. Cui); yfwang@cycu.edu.tw (Y.F. Wang)

system and significantly decrease the lung function index of the human body (Chen *et al.*, 2011). A high atmospheric content of O₃ is highly oxidizing and phytotoxic, which can adversely affect plant growth and human health (Monks *et al.*, 2015). In addition, as the third largest greenhouse gas, O₃ may play an important role in global warming (Stocker *et al.*, 2013). The impact of air pollution on human health and the environment makes air quality a significant issue for the Chinese government and the public.

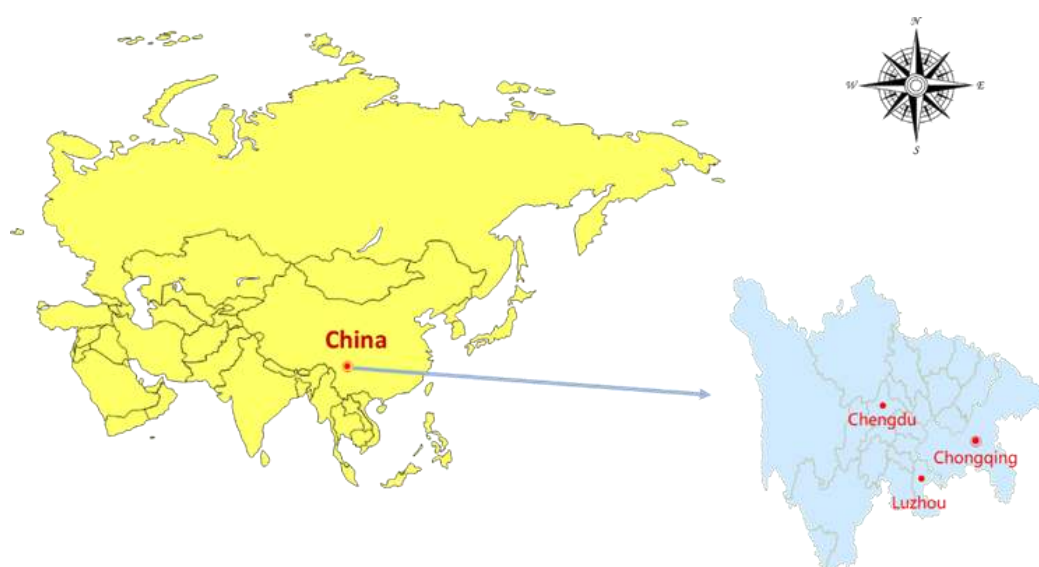
A novel coronavirus outbreak occurred in December 2019. It gradually spread all over the world after Spring 2020. It has been confirmed that this pneumonia is an acute respiratory infectious disease, and it considered new coronavirus pneumonia. On February 11, 2020, the World Health Organization (WHO) named it "COVID-19." On January 31st, 2020, novel coronavirus pneumonia was declared an "international emergency public health incident" by WHO's director general, Tedros Adhanom Ghebreyesus. According to real-time statistical data from Johns Hopkins University in the United States, as of 05:30 on June 5, 2020, Beijing time, the number of confirmed cases of COVID-19 globally was 6,589,090 cases and there had been 388,499 deaths (<https://news.sina.com.cn/world/>). The Chinese government took prompt measures to suspend all types of transportation channels in Wuhan on January 23, 2020, which greatly restricted the flow of people in the area. Subsequently, various provinces and cities launched a first-class emergency response to major public health emergencies, and human activities such as commercial trade, industrial production and transportation decreased dramatically. In order to understand the impact of the COVID-19 epidemic on air quality, this study investigated changes in air quality in Chongqing, Luzhou and Chengdu during the non-epidemic period (January and February 2017–2019) and compared them to the air quality during the epidemic prevention and control period (January and February 2020).

The AQI (Air Quality Index), describes the level of air cleanliness or pollution as well as the impact of air quality on health. This study investigated, compared, and discussed the AQIs and air pollutants PM_{2.5}, PM₁₀, SO₂, NO₂, CO, O₃, and in Chongqing, Luzhou and Chengdu, near western China from 2017 to 2020 focusing on the impacts of epidemic prevention and control actions on air quality.

METHODS

In this study, the air quality in three cities in western China, the Chongqing municipality (longitude 106.54, latitude 29.40), Luzhou in Sichuan province (longitude 105.44, latitude 28.88) and Chengdu (longitude 104.10, latitude 30.66) (Fig. 1) was studied and analyzed for the months of January and February from 2017 to 2020. Chongqing is located in the upper reaches of the Yangtze river, and is characterized by a mild climate and subtropical monsoon humid climate. Chongqing is foggy, and is known as "fog Chongqing." In this study, Spring is defined as the months of March, April, and May; summer includes June, July, and August, and autumn includes September, October, and November, and winter includes January, February and December. The average temperature in Chongqing from 2017 to 2019 ranged between 2.0 and 40°C and averaged 19.6°C; the temperature in spring ranged between 6.0 and 37°C and averaged 20°C; in summer, the temperature ranged between 18 and 40°C and averaged 29°C; in autumn, the temperature ranged between 7.0 and 39°C and averaged 19°C; and in winter, the temperature ranged between 2.0 and 20°C and averaged 10°C.

Located southeast of Sichuan province, Luzhou has a mild subtropical humid climate and four distinct seasons. The average temperature in Luzhou from 2017 to 2019 ranged between -2.0 and 39°C and averaged 18.7°C; the temperature in spring ranged between 4.0 and 36°C and averaged 20°C; in summer, the temperature ranged between 17 and 39°C and



Sichuan Province and Chongqing municipality in China

Fig. 1. Location of Chongqing, Luzhou and Chengdu in Sichuan Province, China.

averaged 28°C; in autumn, the temperature ranged between 6.0 and 35°C and averaged 18.5°C; and in winter, the temperature ranged between –2.0 and 22°C and averaged 9.0°C.

Chengdu is located in the central part of Sichuan province and the western part of the Sichuan basin. It has a subtropical monsoon climate and a warm winter climate. The average temperature in Chengdu from 2017 to 2019 ranged between –5.0 and 36°C and averaged 17.3°C; the temperature in spring ranged between 4.0 and 35°C and averaged 18°C; in summer, the temperature ranged between 17 and 36°C and averaged 26°C; in autumn, the temperature ranged between 1.0 and 34°C and averaged 17°C, and in winter, the temperature ranged between –5.0 and 21°C and averaged 8.0°C.

Air Quality Index (AQI)

The AQI is a dimensionless index that quantitatively describes the air quality status. First, the sub-AQI of six standard pollutants (PM_{2.5}, PM₁₀, SO₂, CO, NO₂ and O₃) is calculated based on the observed concentration, as shown in Eq. (1) (Shen et al., 2017; She et al., 2017). The overall AQI represents the maximum value of the sub-AQI of all pollutants. When the AQI is higher than 50, the highest contributor of the sub-AQI of the day is defined as the primary pollutant, as shown in Eq. (2) (Shen et al., 2017; She et al., 2017):

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

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

$IAQI_p$: the air quality sub index for air pollutant p ;

C_p : the concentration of pollutant p ;

C_{low} : the concentration breakpoint that is $\leq C_p$;

C_{high} : the concentration breakpoint that is $\geq C_p$;

I_{low} : the index breakpoint corresponding to C_{low} ;

I_{high} : the index breakpoint corresponding to C_{high} .

The six standards for air pollutants have serious implications for human health. The daily AQI value is calculated from the average concentration of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO for 24 hours, and the maximum concentration of O₃ eight hours per day. According to the U.S. Environmental Protection Agency (U.S. EPA) AQI, the range of AQI values related to air quality can be divided into six classes (Hu et al., 2015; Lanzafame et al., 2015; She et al., 2017; Zhao et al., 2018):

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.

Wind Streamline and Wind Speed

In order to understand the pathway of airflow in Chongqing Municipality and Sichuan Province from January to March, we chose GrADS (Grid Analysis and Display System,

<http://cola.gmu.edu/grads/>) to compute and draw the distribution of the monthly average near-surface streamlines and wind speed with NCEP GDAS/FNL 0.25 Degree Global Tropospheric Analyses data (<https://rda.ucar.edu/datasets/ds083.3/>).

RESULTS AND DISCUSSION

Distribution of AQI Values

As showed in Fig. 2, in Chongqing, the monthly AQI averages from 2017–2019 ranged between 54.0–98.8, and averaged 73.8, where the three months with the highest average AQIs in order were 98.8, 93.0, and 89.9 in January, August, and December, respectively. In January, the proportions of AQI classes I, II, III, IV, V, and VI were 0%, 42%, 58%, 0%, 0% and 0%, respectively. In August, they were 3%, 55%, 42%, 0%, 0%, and 0%, respectively, and in December, they were 0%, 65%, 35%, 0%, 0%, and 0%, respectively. The three months with the lowest AQIs in order were 65.2, 59.2 and 54.0 in March, September and October, respectively. In March, the proportions of AQI classes I, II, III, IV, V, and VI were 3%, 97%, 0%, 0%, 0%, and 0%, respectively; in September, they were 37%, 63%, 0%, 0%, 0%, and 0%, and in October were 42%, 58%, 0%, 0%, 0% and 0%, respectively. It can be seen that the average monthly average AQI of the highest three months was 93.6, which was 36.5% higher than the average monthly average AQI of the lowest three months (59.5). During the three months with the highest average AQIs, the average proportions of AQI class I, II, III, IV, V, and VI were 1%, 54%, 45%, 0%, 0%, and 0% respectively, those were 27.3%, 72.7%, 0%, 0%, 0%, and 0% during the three months with the lowest average AQIs, compared with the three months with the highest average AQI, the combined average proportions of class I and II in the three months with the lowest average AQI increased by 45.0%, and the class III decreased to zero.

As shown in Fig. 3, in Luzhou, the monthly average AQI values in 2017–2019 ranged between 46.6 and 115, and averaged 73.2, where the three months with the highest average AQIs in order were 115, 89.1, and 88.9 in January, February and December, respectively. The proportions of AQI classes I, II, III, IV, V, and VI in January were 0%, 23%, 74%, 0%, 0%, and 0%, respectively; in February, they were 0%, 75%, 25%, 0%, 0%, and 0%, respectively, and in December, they were 0%, 77%, 23%, 0%, 0%, and 0%, respectively. The three months with the lowest AQIs in order were 61.6, 52.0, and 46.6 in June, September, and October, respectively. The proportions of AQI classes I, II, III, IV, V, and VI in June were 37%, 60%, 3%, 0%, 0%, and 0%; in September, they were 47%, 53%, 0%, 0%, 0%, and 0%, while those in October were 74%, 26%, 0%, 0%, 0%, and 0%, respectively. It can be seen that the average monthly average AQI of the highest three months was 97.7, and was 45.3% higher than the average monthly average AQI of the lowest three months (53.4). During the three months with the highest average AQIs, the average proportions of AQI class I, II, III, IV, V, and VI were 0%, 58.3%, 40.7%, 0%, 0%, and 0% respectively, those were 52.7%, 46.3%, 1.0%, 0%, 0%, and 0% during the three months with the lowest average

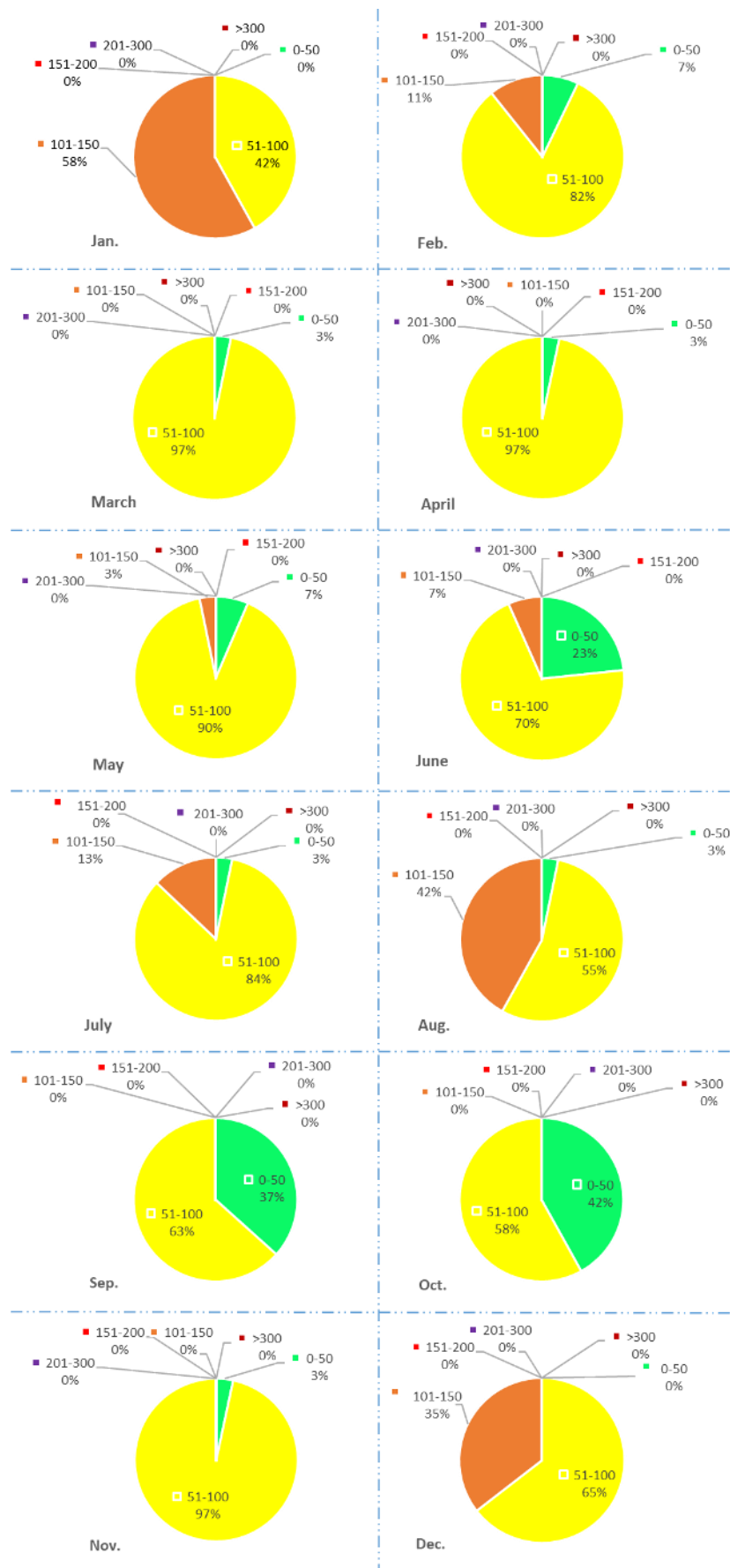


Fig. 2. Average monthly distribution of AQI in Chongqing from 2017 to 2019.

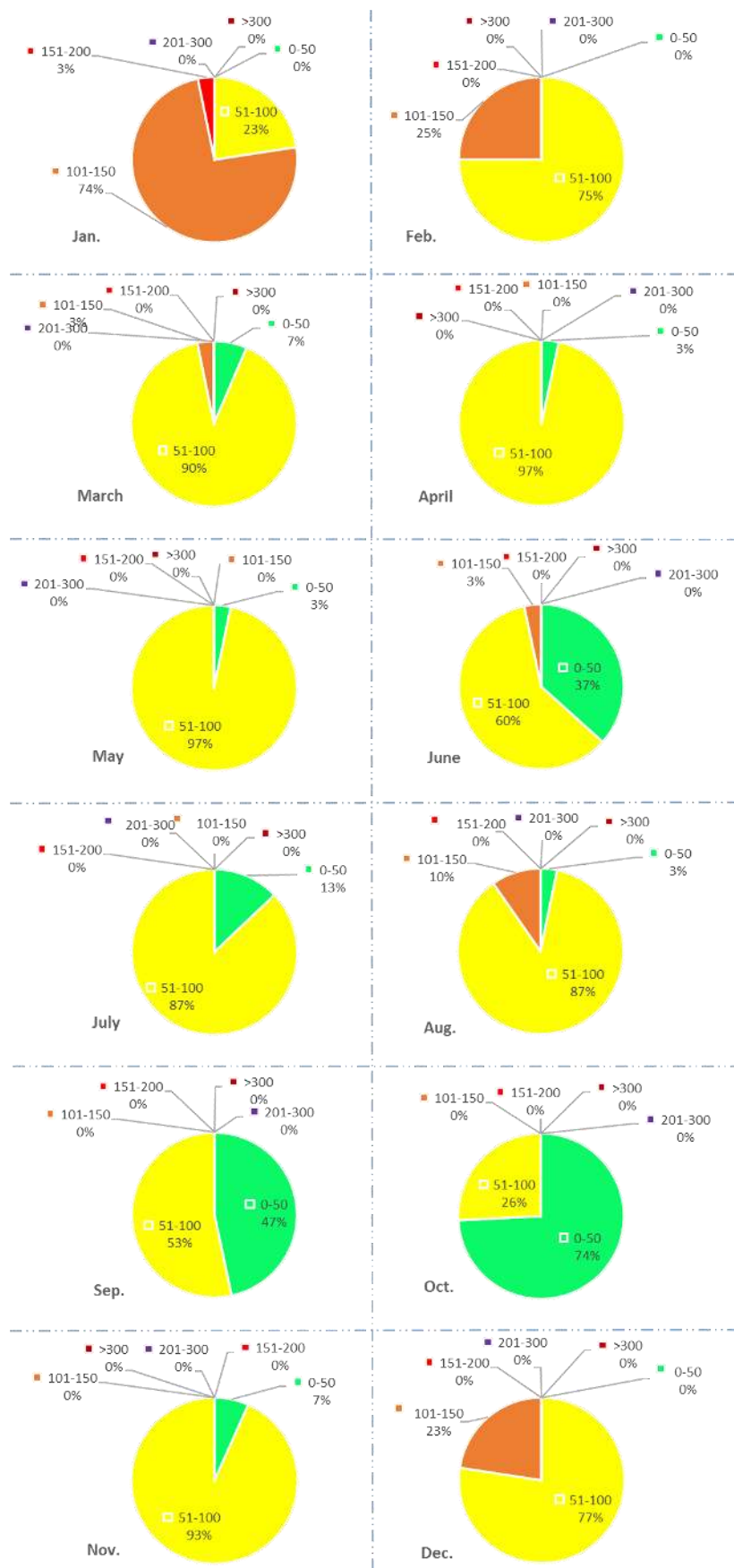


Fig. 3. Average monthly distribution of AQI in Luzhou from 2017 to 2019.

AQIs, compared with the three months with the highest average AQI, the combined average proportions of class I and II in the three months with the lowest average AQI increased by 41.1%, and the class III decreased by 97.5%.

As shown in Fig. 4, in Chengdu, the monthly average AQI values in 2017–2019 ranged between 58.1 and 128, and averaged 85.4, and the three months with the highest AQIs in order were 128, 113, and 96.1 in January, December, and February, respectively; the proportions of AQI classes I, II, III, IV, V, and VI in January were 0%, 16%, 61%, 23%, 0%, and 0%, respectively; in December, they were 0%, 29%, 71%, 0%, 0%, and 0%, respectively, and in February, they were 0%, 64%, 32%, 4%, 0%, and 0%, respectively. The three months with the lowest AQIs in order were 76.1, 61.2, and 58.1 in June, October, and September, respectively; the proportions of AQI classes I, II, III, IV, V, and VI in June were 13%, 70%, 17%, 0%, 0%, and 0%; in October, they were 19%, 81%, 0%, 0%, 0%, and 0%; and those in September were 30%, 70%, 0%, 0%, 0%, and 0%, respectively. It can be seen that the average monthly average AQI of the highest three months was 112, which was 42.0% higher than the average monthly average AQI of the lowest three months (65.1). During the three months with the highest average AQIs, the average proportions of AQI class I, II, III, IV, V, and VI were 0%, 36.3%, 54.7%, 9%, 0%, and 0% respectively, those were 20.7%, 73.7%, 5.7%, 0%, 0%, and 0% during the three months with the lowest average AQIs, compared with the three months with the highest average AQI, the combined average proportions of class I and II in the three months with the lowest average AQI increased by 61.5%, the class III decreased by 89.6%, and the class IV decreased to zero.

According to the above results, in 2017–2019, in Chongqing, the daily AQIs ranged between 27 and 204 and averaged 73.8; in Luzhou, the daily AQIs ranged between 22.7 and 208 and averaged 73.2, and in Chengdu, the daily AQIs ranged between 28.2 and 270 and averaged 85.4. The average AQIs in order were Chengdu (85.4) > Chongqing (73.8) > Luzhou (73.2).

In 2017–2019, in Chongqing, in spring, the daily AQIs ranged between 29 and 145 and averaged 66.6; in summer, those ranged between 30 and 203 and averaged 79.9; in autumn, those ranged between 25 and 132 and averaged 59.9, and in winter, those ranged between 28 and 220 and averaged 88.6. It can be seen that the average AQI was the highest in winter and the lowest was in autumn. In Luzhou, in spring, the daily AQIs ranged between 25 and 165 and averaged 69.3; in summer, those ranged between 24 and 177 and averaged 70.2; in autumn, those ranged between 22 and 134 and averaged 55.6, and in winter, those ranged between 28 and 258 and averaged 97.5. It can be seen that the average AQI was the highest in winter and was the lowest in autumn. In Chengdu, in spring, the daily AQIs ranged between 29 and 182 and averaged 80.3, in summer, those ranged between 28 and 206 and averaged 82.3; in autumn, those ranged between 27 and 170 and averaged 67.9, and in winter, those ranged between 32 and 375 and averaged 113. The seasonal distribution of the highest and lowest average AQIs in Chengdu were consistent with those in Chongqing and Luzhou.

In terms of the combined AQIs for the three cities, in spring, the daily AQIs ranged between 25 and 182 and averaged 72.1; in summer, the daily AQIs ranged between 24 and 206 and averaged 77.5; in autumn, the daily AQIs ranged between 22 and 170 and averaged 61.1, and in winter, the daily AQIs ranged between 28 and 375 and averaged 99.6. The distributions of the six AQI classes, in order, in spring were 3%, 94%, 3%, 0%, 0%, and 0%, respectively; those in summer were 11%, 74%, 15%, 0%, 0% and 0%, respectively; those in autumn were 29%, 70%, 1%, 0%, 0%, and 0%, respectively; and those in winter were 1%, 52%, 44%, 3%, 0%, and 0%, respectively.

According to the data for the three cities, the average AQI in winter was much higher than in other seasons. This is because the temperature in winter is low, and the atmospheric temperature inversion phenomenon is very dominant, which is not conducive to the, dispersion, dilution and diffusion of pollutants in the air, so the average AQI in winter is higher (Xu *et al.*, 2020a, b).

The Top Five Days with the Highest AQIs from 2017 to 2019

Tables 1, 2, and 3 show the top five days with the highest AQIs each year from 2017 to 2019 in Chongqing, Luzhou and Chengdu, and the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃, respectively.

In Table 1, the top five days with the highest AQIs in Chongqing in 2017 were 220, 207, 202, 202 and 202, on January 4, January 3, January 5, December 27, and December 28, respectively. On January 4, 2017, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 171 μg m⁻³, 231 μg m⁻³, 11.2 ppb, 1.36 ppm, 36.5 ppb, respectively, and on December 28, they were 156 μg m⁻³, 229 μg m⁻³, 4.9 ppb, 1.52 ppm, 33.1 ppb, and 9.33 ppb, respectively. The indicative air pollutant on all of these days was PM_{2.5}. The highest AQIs in 2018 were 190, 178, 172, 168, and 163, on January 13, December 19, June 7, January 15, and January 14, respectively. On January 13, 2018, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 143 μg m⁻³, 205 μg m⁻³, 7.35 ppb, 1.12 ppm, 37.5 ppb, and 3.73 ppb, respectively, and on January 14, they were 124 μg m⁻³, 174 μg m⁻³, 5.95 ppb, 1.04 ppm, 35.1 ppb and 21.5 ppb respectively. The indicative air pollutants on these five days were PM_{2.5}, PM_{2.5}, O₃, PM_{2.5}, and PM_{2.5}, respectively. The highest AQIs in 2019 were 203, 179, 175, 172, and 166, on August 12, August 15, January 26, August 17, and August 16, respectively. On August 12, 2019, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 26 μg m⁻³, 55 μg m⁻³, 2.8 ppb, 0.64 ppm, 21.4 ppb, and 129 ppb, respectively, and on August 16, they were 28 μg m⁻³, 57 μg m⁻³, 3.50 ppb, 0.56 ppm, 21.9 ppb, and 108 ppb, respectively, and the indicative air pollutants for these five days were O₃, O₃, PM_{2.5}, O₃ and O₃, respectively. The most common indicative air pollutant in summer was O₃, but, in winter, it was PM_{2.5}. Previous studies have shown that atmospheric relative humidity is negatively correlated with O₃ concentration and that a lower relative humidity is conducive to the formation of O₃ (Kato *et al.*, 2016; Li *et al.*, 2017b; Gong *et al.*, 2018). In summer, low relative humidity and high temperatures and

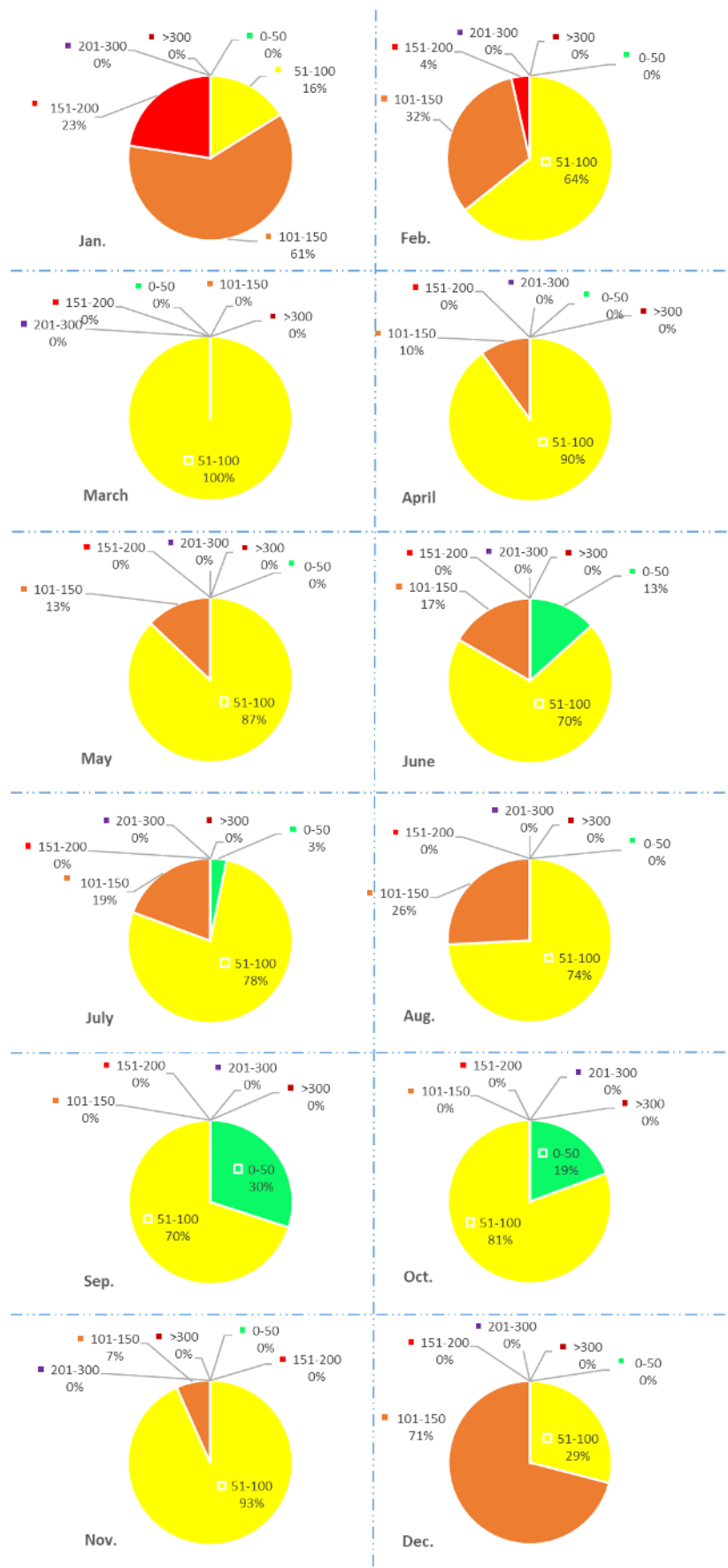


Fig. 4. Average monthly distribution of AQI in Chengdu from 2017 to 2019.

Table 1. The five days with the highest AQIs each year in Chongqing in 2017–2019.

Date	AQI	PM _{2.5} (μg m ⁻³)	PM ₁₀ (μg m ⁻³)	SO ₂ (ppb)	CO (ppm)	NO ₂ (ppb)	O ₃ (ppb)
Jan. 4, 2017	220	171	231	11.2	1.36	36.5	4.20
Jan. 3, 2017	207	157	214	7.35	1.52	36.0	4.67
Dec. 27, 2017	202	155	213	5.60	1.52	33.1	8.87
Dec. 28, 2017	202	156	229	4.90	1.52	33.1	9.33
Jan. 5, 2017	202	152	205	7.00	1.20	31.7	6.07
Jan. 13, 2018	190	143	205	7.35	1.12	37.5	3.73
Dec. 19, 2018	178	134	179	5.25	1.12	29.7	3.27
June. 7, 2018	172	34	64	3.85	0.72	25.3	111
Jan. 15, 2018	168	127	186	5.95	1.20	40.4	6.53
Jan. 14, 2018	163	124	174	5.95	1.04	35.1	21.5
Aug. 12, 2019	203	26	55	2.80	0.64	21.4	129
Aug. 15, 2019	179	29	54	2.80	0.72	18.0	114
Jan. 26, 2019	175	132	177	3.50	0.96	26.8	6.53
Aug. 17, 2019	172	27	56	4.20	0.64	22.9	111
Aug. 16, 2019	166	28	57	3.50	0.56	21.9	108

wind speeds are conducive to the dispersion, diffusion, and dilution of air pollutants. Precursors (VOCs) also promote the formation of O₃. In addition, high temperatures and strong ultraviolet radiation will increase the production rate of O₃ in summer; therefore, the concentration of O₃ in summer is much higher. In winter, a large amount of coal was used, and the exhaust gas from combustion greatly contributed to an increase in the concentration of atmospheric particulate matter. By contrast, the temperature in winter is low, and the inverse temperature phenomenon is prominent, which hinders the dilution and diffusion of pollutants in the air. Therefore, the PM_{2.5} concentration in winter is higher.

In Table 2, for the top five days with the highest AQIs in Luzhou, in 2017, the AQIs were 258, 247, 237, 233, and 224, on January 24, January 4, January 26, December 27, and January 3, respectively. On January 24, 2017, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 208 μg m⁻³, 266 μg m⁻³, 8.75 ppb, 0.96 ppm, 21.9 ppb, and 22.4 ppb, respectively, and on January 3, they were 174 μg m⁻³, 236 μg m⁻³, 12.0 ppb, 0.80 ppm, 28.2 ppb, and 5.13 ppb, respectively, where the indicative air pollutant for all five days was PM_{2.5}. The highest AQIs in 2018 were 188, 183, 168, 166, and 165, on January 15, January 13, January 12, December 19, and February 16, respectively. On January 15, 2018, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 141 μg m⁻³, 188 μg m⁻³, 11.6 ppb, 0.88 ppm, 27.3 ppb, and 7.93 ppb, respectively, and on February 16, they were 125 μg m⁻³, 171 μg m⁻³, 6.65 ppb, 0.64 ppm, 14.6 ppb, and 42.9 ppb, respectively, where the indicative air pollutant on all five days was PM_{2.5}. The highest AQIs in 2019 were 179, 177, 165, 159, and 156 on January 28, August 17, March 13, January 25, and January 8, respectively. On January 28, 2019, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 135 μg m⁻³, 164 μg m⁻³, 3.85 ppb, 0.80 ppm, 22.9 ppb, and 10.3 ppb, respectively, and on January 8, they were 119 μg m⁻³, 147 μg m⁻³, 8.75 ppb, 0.80 ppm, 21.9 ppb, and 9.33 ppb, respectively. The indicative air pollutants for these five days were PM_{2.5}, O₃, PM_{2.5}, PM_{2.5} and PM_{2.5}, respectively. According to an analysis of the observation data for three years in Luzhou, the days with

higher AQIs were mainly in winter, particularly in January, and the indicative air pollutant was mainly PM_{2.5}, which is consistent with the findings for Chongqing.

In Table 3, the highest AQIs in Chengdu in 2017 were 375, 308, 294, 274, and 248, on January 5, January 4, January 6, January 26, and January 27, respectively. On January 5, 2017, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 313 μg m⁻³, 480 μg m⁻³, 7.00 ppb, 2.24 ppm, 58.9 ppb, and 21.5 ppb, respectively, and on January 27, they were 198 μg m⁻³, 308 μg m⁻³, 4.55 ppb, 1.28 ppm, 25.3 ppb, and 32.2 ppb, respectively. The indicative air pollutant for all five days was all PM_{2.5}. The highest AQIs in 2018 were 251, 207, 206, 205, and 192 on January 15, January 14, February 16, December 20, and December 19, respectively. On January 15, 2018, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 201 μg m⁻³, 269 μg m⁻³, 6.65 ppb, 1.28 ppm, 42.9 ppb, and 7.93 ppb, respectively, and on December 19, they were 144 μg m⁻³, 195 μg m⁻³, 2.80 ppb, 0.96 ppm, 33.6 ppb, and 11.2 ppb, respectively. The indicative air pollutant for all five days was PM_{2.5}. The highest AQIs in 2019 were 185, 183, 178, 174, 173, and 173 on six days comprising August 12, December 13, December 11, August 17, December 12, and December 14, respectively. On August 12, 2019, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 40 μg m⁻³, 80 μg m⁻³, 2.80 ppb, 0.72 ppm, 26.3 ppb, and 117 ppb, respectively; on December 12, they were 131 μg m⁻³, 167 μg m⁻³, 4.20 ppb, 0.96 ppm, 28.7 ppb, and 9.80 ppb, respectively, and on December 14, they were 131 μg m⁻³, 171 μg m⁻³, 3.50 ppb, 0.96 ppm, 31.7 ppb, and 7.00 ppb, respectively. The indicative air pollutants on these six days were O₃, PM_{2.5}, PM_{2.5}, O₃, PM_{2.5}, and PM_{2.5}, respectively. According to the analysis of the observation data for three years, in Chengdu, the days with higher AQI occurred mainly in winter, particularly in January and December, where the indicative air pollutant was mainly PM_{2.5}, which was consistent with the findings for both Chongqing and Luzhou.

According to Table 3, in Chongqing, the top five highest AQIs in 2017 occurred mainly in January and December. In 2018, they occurred mainly in January, June, and December,

Table 2. The five days with the highest AQIs in each year in Luzhou in 2017–2019.

Date	AQI	PM _{2.5} (μg m ⁻³)	PM ₁₀ (μg m ⁻³)	SO ₂ (ppb)	CO (ppm)	NO ₂ (ppb)	O ₃ (ppb)
Jan. 24, 2017	258	208	266	8.75	0.96	21.9	22.4
Jan. 4, 2017	247	200	257	16.8	0.56	21.9	5.13
Jan. 26, 2017	237	190	243	8.05	0.96	23.4	4.67
Dec. 27, 2017	233	183	256	9.80	1.52	40.9	4.67
Jan. 3, 2017	224	174	236	12.0	0.80	28.2	5.13
Jan. 15, 2018	188	141	188	11.6	0.88	27.3	7.93
Jan. 13, 2018	183	138	187	14.0	0.80	27.3	7.93
Jan. 12, 2018	168	127	177	12.0	0.80	31.7	7.47
Dec. 19, 2018	166	126	149	10.1	0.80	21.4	5.60
Feb. 16, 2018	165	125	171	6.65	0.64	14.6	42.9
Jan. 28, 2019	179	135	164	3.85	0.80	22.9	10.3
Aug. 17, 2019	177	40	67	6.30	0.56	21.4	113
Mar. 13, 2019	165	125	152	6.65	0.80	25.8	8.40
Jan. 25, 2019	159	121	147	6.65	0.80	23.4	14.0
Jan. 8, 2019	156	119	147	8.75	0.80	21.9	9.33

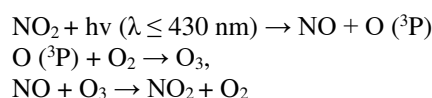
Table 3. The five days with the highest AQIs each year in Chengdu in 2017–2019.

Date	AQI	PM _{2.5} (μg m ⁻³)	PM ₁₀ (μg m ⁻³)	SO ₂ (ppb)	CO (ppm)	NO ₂ (ppb)	O ₃ (ppb)
Jan. 5, 2017	375	313	480	7.00	2.24	58.9	21.5
Jan. 4, 2017	308	258	399	10.2	1.92	54.5	5.13
Jan. 6, 2017	294	243	360	6.30	1.84	41.4	7.93
Jan. 26, 2017	274	227	316	4.90	1.36	34.1	20.1
Jan. 27, 2017	248	198	308	4.55	1.28	25.3	32.2
Jan. 15, 2018	251	201	269	6.65	1.28	42.9	7.93
Jan. 14, 2018	207	157	213	6.30	1.04	37.0	35.5
Feb. 16, 2018	206	156	193	3.85	1.04	18.0	49.5
Dec. 20, 2018	205	155	207	3.50	0.96	27.8	10.3
Dec. 19, 2018	192	144	195	2.80	0.96	33.6	11.2
Aug. 12, 2019	185	40	80	2.80	0.72	26.3	117
Dec. 13, 2019	183	138	170	3.50	0.96	27.3	7.93
Dec. 11, 2019	178	134	178	3.15	1.04	33.1	21.0
Aug. 17, 2019	174	43	80	2.80	0.72	28.2	112
Dec. 12, 2019	173	131	167	4.20	0.96	28.7	9.80
Dec. 14, 2019	173	131	171	3.50	0.96	31.7	7.00

while in 2019, they were mainly in January and August. In Luzhou, the top five highest AQIs in 2017 occurred mainly in January and December. In 2018, they occurred mainly in January, February, and December, while in 2019, they were mainly in January, March, and August. In Chengdu, the top five highest AQIs in 2017 occurred mainly in January, in 2018, they were mainly in January, February, and December, and in 2019, the top six highest AQIs were mainly in August and December.

Among the 46 days with the highest AQIs over the three years under observation (2017–2019), the distributions were 52.0%, 24.0%, 17.0%, 4.30%, and 2.20% in January, December, August, February, and June, respectively. It can be seen that the highest AQIs occurred mainly in the season with lower temperatures (January, December, and February), which was consistent with the conclusion made earlier that PM_{2.5} was the main indicatory air pollutant in January, February, and December due to low temperatures, and O₃ was the main air pollutant in June and August due to hot temperatures. In winter, a lower ground temperature will

hinder the dispersion of air pollutants and lead to an increase in PM_{2.5} concentrations in the atmosphere (Tang *et al.*, 2017; Xing *et al.*, 2017; Lee *et al.*, 2018; Wang *et al.*, 2018). Under sufficient solar radiation intensity, NO₂ acts as the precursor of a photochemical reaction, and first decomposes into NO and O (³P):



It can be seen that NO_x is one of the important precursors of O₃, and NO is a direct reactant with O₃. A lower NO₂ concentration in the atmosphere will lead to a decrease in the level of NO, which will reduce the possibility of NO reacting with O₃, and in turn will lead to an accumulation of O₃. Due to strong solar radiation and a dominant photochemical reaction, summer is more suitable for the accumulation of O₃. Therefore, O₃ concentrations in summer are much higher. The average AQIs during the 15 days with highest

AQIs were 187, 194, and 227 in Chongqing, Luzhou, and Chengdu, respectively. These results indicate that Chengdu had the highest average AQI during the observation period, and thus more attention should be paid to improving the air quality in this city.

It can be seen that the average AQIs in Chengdu (227) were far greater than the average AQI values in Chongqing and Luzhou, while the results in Chongqing (187) and Luzhou (194) were very close. It can be concluded that the air quality in Chengdu was the worst, and the air quality in Chongqing and Luzhou were, in order, the second and the third. This result is consistent with conclusions drawn above.

In Chongqing, the average AQI values for the highest five days were 207, 174, and 179 in 2017, 2018, and 2019, respectively; in Luzhou, they were 240, 174, and 167, and in Chengdu, they were 300, 212 and 178 in 2017, 2018 and 2019, respectively. It can be seen that in Chongqing, the air quality was the worst in 2017, followed by 2019, and was the best in 2018; in Luzhou, the air quality was the worst in 2017, followed by 2018, and was the best in 2019; in Chengdu, the air quality was the worst in 2017, followed by 2018, and was the best in 2019. From 2017 to 2019, in general, the air quality of the three cities were all improved.

Impact of the COVID-19 Event on Air Quality

Figs. 2, 3, and 4 show the average monthly AQI distribution for Chongqing, Luzhou and Chengdu in January and February 2017–2019 during the non-epidemic period, respectively, and Fig. 5 shows the monthly AQI distribution in Chongqing, Luzhou and Chengdu in January and February 2020 for the epidemic prevention and control period.

As shown in Figs. 2 and 5, in Chongqing, the proportion of classes I, II, III, IV, V, and VI with the average AQI from January 2017–2019 were 0%, 42%, 58%, 0%, 0%, and 0%, respectively, and those in January 2020, were 19%, 74%, 7%, 0%, 0%, and 0%, respectively. It can be seen that compared with the average AQI from January 2017–2019, the proportion of Class I in January 2020 increased to 19.0%; that of Class II increased to 74.0%, and that of Class III decreased to 7.00%. In addition, the average AQI in January 2020 was 69.8, which was 35.7% lower than that in 2017–2019 (AQI = 98.8). In February 2017–2019, in Chongqing, the proportion of classes I, II, III, IV, V, and VI with the average AQI was 7%, 82%, 11%, 0%, 0%, and 0% respectively, and in February 2020, the proportion of classes I, II, III, IV, V, and VI with the average AQI was 21%, 65%, 14%, 0%, 0%, and 0%, respectively. It can be seen that compared with the average AQI in February 2017–2019, Class I in February 2020 increased to 21.0%, and Class II decreased to 65.0%. The average AQI in February 2020 was 68.8, which was 11.5% lower than that from 2017–2019 (AQI=77.2). It can be seen that the air quality in January and February 2020 (during the epidemic prevention and control period) improved significantly compared with January and February 2017–2019 (the non-epidemic period).

As shown in Figs. 3 and 5, in Luzhou, the proportion of classes I, II, III, IV, V and VI with the average AQI in January 2017–2019 was 0%, 23%, 74%, 3%, 0%, and 0%, respectively, and these classes in January 2020, were 10%,

61%, 29%, 0%, 0%, and 0%, respectively. It can be seen that compared with the average AQI in January 2017–2019, the AQI Class I in January 2020 increased to 10.0%; Class II increased to 61.0%; Class III decreased to 29.0%, and Class IV decreased to zero. The average AQI in January 2020 was 87.0, which was 27.4% lower than that in the period 2017–2019 (AQI = 115). In February 2017–2019, the proportions of classes I, II, III, IV, V, and VI were 0%, 75%, 25%, 0%, 0%, and 0%, respectively, and those in February 2020, were 7%, 62%, 31%, 0%, 0% and 0%, respectively. It can be seen that compared with the average AQI in February 2017–2019, AQI Class I in February 2020 increased to 7.00%, and AQI Class II decreased to 62.0%. The average AQI in February 2020 was 83.5, which was 6.50% lower than that in the period 2017–2019 (AQI=89.1). It can be seen that the air quality in January and February 2020 (during the epidemic prevention and control period) improved significantly compared with January and February 2017–2019 (the non-epidemic period).

As shown in Figs. 4 and 5, in Chengdu, the proportion of classes I, II, III, IV, V, and VI with the average AQI in January 2017–2019 was 0%, 16%, 61%, 23%, 0%, and 0%, respectively, and the proportion of classes I, II, III, IV, V and VI with the average AQI in January 2020 was 0%, 58%, 39%, 3%, 0%, and 0%, respectively. It can be seen that compared with the average AQI in January 2017–2019, the proportion of AQI Class II in January 2020 increased to 58.0%, and that of Class III decreased to 39.0%. The average AQI in January 2020 was 92.9, which was 32.0% lower than that from 2017–2019 (AQI=128). In Chengdu, the proportion of classes I, II, III, IV, V, and VI with the average AQI in February 2017–2019 was 0%, 64%, 32%, 4%, 0%, and 0%, respectively, and the proportion in February 2020 was 17%, 59%, 24%, 0%, 0%, and 0%, respectively. It can be seen that compared with the average AQI in February 2017–2019, AQI Class I in February 2020 increased to 17.0%; Class II decreased to 59.0%; Class III decreased to 24.0%, and Class IV decreased to zero. The average AQI in February 2020 was 74.7, which was 25.0% lower than that during the period from 2017–2019 (AQI=96.0). It can be seen that the AQI in January and February 2020 (during the epidemic prevention and control period) decreased significantly compared with January and February 2017–2019 (during the non-epidemic period).

According to the above analysis, for the three cities, the combined AQI in February 2020 was 79.4, which was 23.6% lower than that in the period from 2017–2019 (AQI = 101). These results indicated that the prevention and control measures for COVID-19 greatly restricted the movement of people, transportation, engineering construction, industrial production and commercial trading activities. Therefore, the stationary emissions, automobile exhaust, and fugitive emissions were also been greatly reduced, so the air quality was significantly improved.

The Five Days with the Highest AQIs in February 2017–2020

Tables 4–6 shows the top five days with the highest AQIs in Chongqing, Luzhou and Chengdu in February 2017–2020.

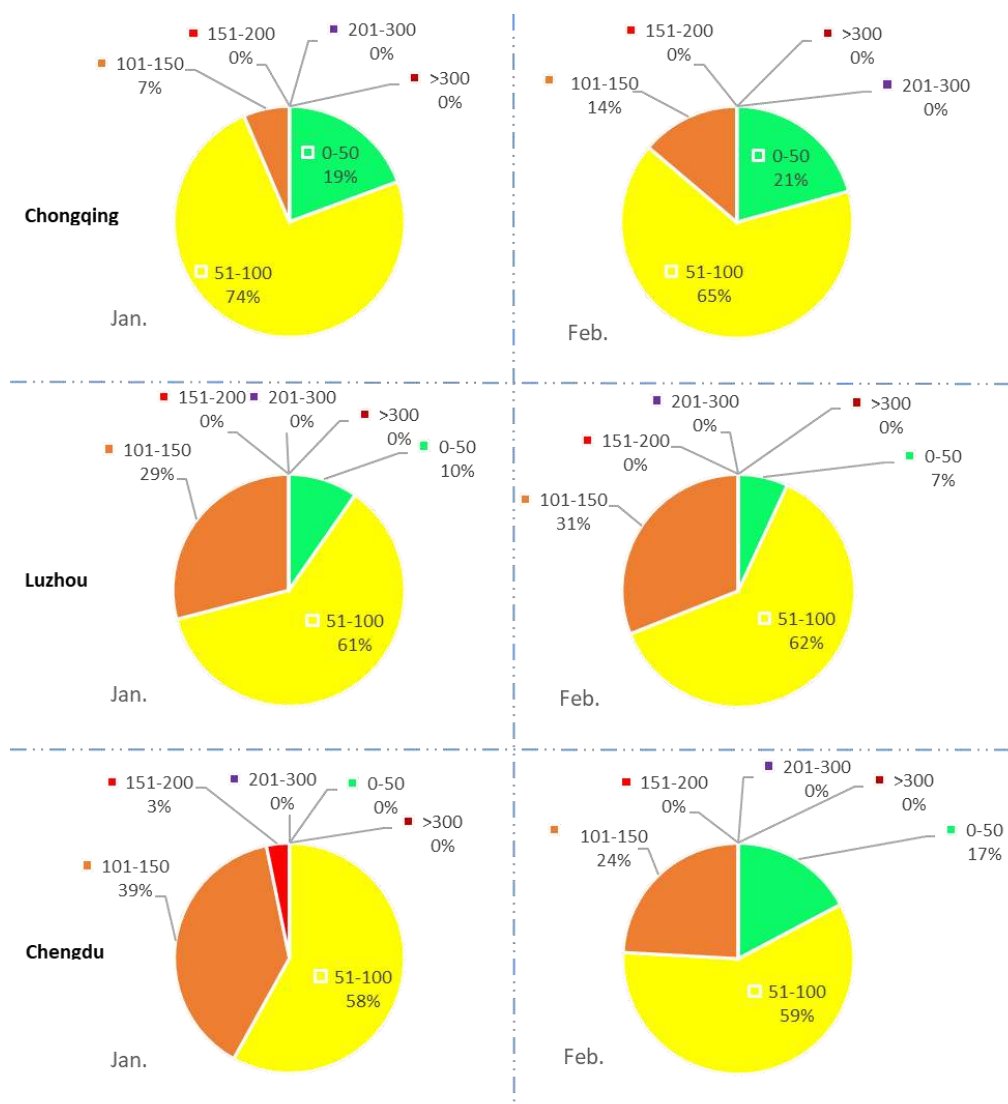


Fig. 5. AQI distribution in January and February 2020 in Chongqing, Luzhou and Chengdu.

As shown in Table 4, in Chongqing, the highest AQIs in February 2017 were 164, 162, 149, 130, and 129 on February 15, February 14, February 18, February 17, and February 19, respectively. On February 15, 2017, the concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $126 \mu\text{g m}^{-3}$, $169 \mu\text{g m}^{-3}$, 6.30 ppb , 1.28 ppm , 34.1 ppb , and 20.1 ppb , respectively, and on February 19, they were $98 \mu\text{g m}^{-3}$, $131 \mu\text{g m}^{-3}$, 4.20 ppb , 1.04 ppm , 23.9 ppb , and 38.3 ppb respectively. The indicative air pollutant on five days was $\text{PM}_{2.5}$.

The highest AQIs on February 2018 in Chongqing were 156, 134, 125, 119, and 112 on February 16, February 7, February 17, February 8 and February 2, respectively. On February 16, 2018, the concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $119 \mu\text{g m}^{-3}$, $150 \mu\text{g m}^{-3}$, 5.95 ppb , 0.96 ppm , 13.6 ppb , and 35.5 ppb , respectively, and on February 2, those were $84 \mu\text{g m}^{-3}$, $128 \mu\text{g m}^{-3}$, 4.90 ppb , 0.88 ppm , 26.8 ppb , and 18.7 ppb , respectively. The indicative air pollutant for all five days was $\text{PM}_{2.5}$.

In Chongqing, the highest AQIs in February 2019 were

113, 103, 97, 88, and 88 on February 21, February 7, February 22, February 5, and February 20, respectively. On February 16, 2019, the concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $85 \mu\text{g m}^{-3}$, $115 \mu\text{g m}^{-3}$, 3.50 ppb , 0.88 ppm , 24.4 ppb , and 28.0 ppb , respectively, and on February 20, they were $65 \mu\text{g m}^{-3}$, $92 \mu\text{g m}^{-3}$, 2.80 ppb , 0.80 ppm , 22.4 ppb , and 24.3 ppb , respectively. The indicative air pollutant for all five days was $\text{PM}_{2.5}$.

The highest AQIs in February 2020 in Chongqing were 113, 113, 105, 102, and 93 on February 19, February 21, February 23, February 14 and February 20, respectively. On February 19, 2020, the concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $85 \mu\text{g m}^{-3}$, $104 \mu\text{g m}^{-3}$, 2.10 ppb , 0.64 ppm , 11.2 ppb , and 35.5 ppb , respectively, and on February 20, they were $69 \mu\text{g m}^{-3}$, $85 \mu\text{g m}^{-3}$, 2.10 ppb , 0.56 ppm , 12.7 ppb , and 21.5 ppb , respectively. The indicative air pollutant on all five days was all $\text{PM}_{2.5}$.

The above results indicated that in Chongqing, the average value on the 15 days with the highest AQI in February 2017–2019 (non-epidemic period) was 125, and the corresponding

Table 4. The top five days with the highest AQIs in Chongqing in February 2017–2020.

Date	AQI	PM _{2.5} (μg m ⁻³)	PM ₁₀ (μg m ⁻³)	SO ₂ (ppb)	CO (ppm)	NO ₂ (ppb)	O ₃ (ppb)
Feb. 15, 2017	164	126	169	6.30	1.28	34.1	20.1
Feb. 14, 2017	162	126	166	8.05	1.12	30.2	8.40
Feb. 18, 2017	149	115	153	6.30	1.12	28.2	18.2
Feb. 17, 2017	130	102	143	7.35	1.12	34.6	28.9
Feb. 19, 2017	129	98	131	4.20	1.04	23.9	38.3
Feb. 16, 2018	156	119	150	5.95	0.96	13.6	35.5
Feb. 7, 2018	134	102	145	4.55	0.88	28.2	15.9
Feb. 17, 2018	125	95	117	4.20	1.04	19.5	16.8
Feb. 8, 2018	119	90	124	4.20	0.80	26.8	25.2
Feb. 2, 2018	112	84	128	4.90	0.88	26.8	18.7
Feb. 21, 2019	113	85	115	3.50	0.88	24.4	28.0
Feb. 7, 2019	103	77	109	4.20	0.80	14.6	41.1
Feb. 22, 2019	97	72	99	3.85	0.88	22.4	21.5
Feb. 5, 2019	88	65	87	4.55	0.72	11.7	42.9
Feb. 20, 2019	88	65	92	2.80	0.80	22.4	24.3
Feb. 19, 2020	113	85	104	2.10	0.64	11.2	35.5
Feb. 21, 2020	113	85	107	2.10	0.56	11.2	21.9
Feb. 23, 2020	105	79	99	2.10	0.80	15.1	10.3
Feb. 14, 2020	102	76	91	2.45	0.72	12.2	35.0
Feb. 20, 2020	93	69	85	2.10	0.56	12.7	21.5

average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 94.7 μg m⁻³, 129 μg m⁻³, 5.00 ppb, 0.95 ppm, 24.1 ppb, and 25.6 ppb respectively. The average AQI on the five days with the highest AQI in February 2020 (the epidemic prevention and control period) was 105, and the corresponding average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 78.8 μg m⁻³, 97.2 μg m⁻³, 2.17 ppb, 0.66 ppm, 12.5 ppb, and 24.8 ppb, and were 18.4%, 27.8%, 78.8%, 37.1%, 63.6%, and 3.00%, lower than those in the period from 2017–2019, respectively. In Table 4, the average AQI in 2020 was 105, which was 16.9% lower than that in the period from 2017–2019 (AQI = 125). Compared with the non-epidemic control period, the air quality in the epidemic prevention and control period was improved significantly.

As shown in Table 5, in Luzhou, the highest AQIs in February 2017 were 177, 170, 168, 162, and 161 on February 18, February 16, February 20, February 14, and February 15, respectively. On February 18, 2017, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 139 μg m⁻³, 188 μg m⁻³, 13.3 ppb, 0.72 ppm, 24.4 ppb, and 30.8 ppb, respectively, and on February 15, they were 122 μg m⁻³, 165 μg m⁻³, 11.2 ppb, 0.56 ppm, 23.9 ppb, and 35.5 ppb, respectively. The indicator air pollutant on all five days was PM_{2.5}.

The highest AQIs in February 2018 in Luzhou were 165, 148, 139, 134, and 122 on February 16, February 15, February 7, February 9, and February 17, respectively. On February 16, 2018, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 125 μg m⁻³, 171 μg m⁻³, 6.65 ppb, 0.64 ppm, 14.6 ppb, and 42.9 ppb, respectively, and on February 17, they were 92 μg m⁻³, 125 μg m⁻³, 7.00 ppb, 0.80 ppm, 17.0 ppb, and 31.3 ppb, respectively. The indicator air pollutant on all five days was PM_{2.5}.

In Luzhou, the highest AQIs in February 2019 were 142, 120, 115, 105, and 105 on February 5, February 22, February

23, February 6, and February 7, respectively. On February 5, 2019, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 108 μg m⁻³, 133 μg m⁻³, 5.60 ppb, 0.72 ppm, 12.7 ppb, and 42.9 ppb, respectively, and on February 7, they were 79 μg m⁻³, 95 μg m⁻³, 4.90 ppb, 0.72 ppm, 13.2 ppb, and 46.2 ppb, respectively. The indicator air pollutant on all five days was PM_{2.5}.

The highest AQIs in February 2020 in Luzhou were 150, 134, 133, 129, and 113 on February 22, February 13, February 18, February 14, and February 20, respectively. On February 22, 2020, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 115 μg m⁻³, 127 μg m⁻³, 2.45 ppb, 0.80 ppm, 9.74 ppb, and 18.2 ppb, respectively, and on February 20, they were 85 μg m⁻³, 94 μg m⁻³, 1.75 ppb, 0.72 ppm, 7.79 ppb, and 26.1 ppb, respectively. The indicator air pollutant on all five days was PM_{2.5}.

According to the above data, it can be seen that in Luzhou, the average AQI on the 15 days with the highest AQI in February 2017–2019 (non-epidemic period) was 142, and the corresponding average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 108 μg m⁻³, 143 μg m⁻³, 7.70 ppb, 0.69 ppm, 18.4 ppb, and 31.7 ppb, respectively. The average AQI on the top five days with the highest AQI in February 2020 (epidemic prevention and control period) was 132, and the corresponding average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 100 μg m⁻³, 113 μg m⁻³, 2.38 ppb, 0.77 ppm, 8.86 ppb, and 30.0 ppb, which were 7.60%, 23.5%, 105.6%, -11.0%, 70.0%, and 5.60% lower than those in 2017–2019, respectively. In Table 5, it can be seen that the average AQI in 2020 was 142, which was 7.60% lower than that in the period from 2017–2019 (AQI = 132). Compared with the non-epidemic period, the air quality in the epidemic prevention and control period improved significantly.

As shown in Table 6, in Chengdu, the highest AQIs in February 2017 were 213, 207, 190, 165, and 164, on February

Table 5. The five days with the highest AQIs in Luzhou in February 2017–2020.

Date	AQI	PM _{2.5} (μg m ⁻³)	PM ₁₀ (μg m ⁻³)	SO ₂ (ppb)	CO (ppm)	NO ₂ (ppb)	O ₃ (ppb)
Feb. 18, 2017	177	139	188	13.3	0.72	24.4	30.8
Feb. 16, 2017	170	130	181	9.80	0.72	26.8	41.5
Feb. 20, 2017	168	126	169	11.9	0.72	22.9	29.9
Feb. 14, 2017	162	123	163	10.5	0.56	19.0	28.5
Feb. 15, 2017	161	122	165	11.2	0.56	23.9	35.5
Feb. 16, 2018	165	125	171	6.65	0.64	14.6	42.9
Feb. 15, 2018	148	113	152	6.65	0.64	15.1	38.3
Feb. 7, 2018	139	106	144	8.05	0.72	18.5	13.1
Feb. 9 2018	134	102	134	6.30	0.56	15.1	24.7
Feb. 17 2018	122	92	125	7.00	0.80	17.0	31.3
Feb. 5, 2019	142	108	133	5.60	0.72	12.7	42.9
Feb. 22, 2019	120	91	114	5.25	0.72	20.5	14.5
Feb. 23, 2019	115	87	107	4.90	0.72	19.5	8.87
Feb. 6, 2019	105	79	97	3.50	0.80	13.2	46.2
Feb. 7, 2019	105	79	95	4.90	0.72	13.2	46.2
Feb. 22, 2020	150	115	127	2.45	0.80	9.74	18.2
Feb. 13, 2020	134	102	113	3.15	0.80	9.25	45.7
Feb. 18, 2020	133	101	123	2.45	0.72	10.7	19.6
Feb. 14, 2020	129	98	106	2.10	0.80	6.82	40.1
Feb. 20, 2020	113	85	94	1.75	0.72	7.79	26.1

Table 6. The five days with the highest AQIs in Chengdu in February 2017–2020.

Date	AQI	PM _{2.5} (μg m ⁻³)	PM ₁₀ (μg m ⁻³)	SO ₂ (ppb)	CO (ppm)	NO ₂ (ppb)	O ₃ (ppb)
Feb. 16, 2017	213	163	224	6.30	1.20	41.4	29.4
Feb. 19, 2017	207	157	226	8.05	1.44	39.0	53.2
Feb. 13, 2017	190	141	198	6.65	0.96	31.2	15.4
Feb. 17, 2017	165	126	177	5.60	1.04	35.1	49.0
Feb. 18, 2017	164	125	188	8.40	1.28	40.9	32.7
Feb. 16, 2018	206	156	193	3.85	1.04	18.0	49.5
Feb. 14, 2018	160	122	183	3.15	0.96	23.4	35.0
Feb. 7, 2018	159	121	156	2.80	0.96	28.7	19.6
Feb. 15, 2018	147	112	152	2.10	1.04	20.9	43.4
Feb. 8, 2018	143	109	132	2.45	0.80	23.9	24.7
Feb. 5, 2019	137	104	140	3.50	0.72	17.5	51.8
Feb. 22, 2019	120	91	131	3.85	1.12	37.5	6.07
Feb. 6, 2019	112	84	116	2.45	0.72	17.0	45.3
Feb. 23, 2019	108	81	112	2.10	0.80	25.8	14.0
Feb. 2, 2019	105	79	98	2.10	0.80	17.5	15.9
Feb. 27, 2020	138	105	125	2.10	0.80	16.6	25.2
Feb. 13, 2020	115	87	96	2.45	0.72	10.2	44.8
Feb. 26, 2020	114	86	110	2.45	0.72	21.4	48.1
Feb. 12, 2020	113	85	99	2.45	0.80	11.7	40.1
Feb. 24, 2020	110	83	108	2.45	0.64	18.5	44.3

16, February 19, February 13, February 17, and February 18, respectively. On February 16, 2017, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 163 μg m⁻³, 224 μg m⁻³, 6.30 ppb, 1.20 ppm, 41.4 ppb, and 29.4 ppb, respectively, and on February 18, they were 125 μg m⁻³, 188 μg m⁻³, 8.40 ppb, 1.28 ppm, 40.9 ppb, and 32.7 ppb respectively. The indicative air pollutant for all five days was PM_{2.5}.

The highest AQIs in February 2018 in Chengdu were 206, 160, 159, 147, and 143 on February 16, February 14, February 7, February 15, and February 8, respectively. On February

16, 2018, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 156 μg m⁻³, 193 μg m⁻³, 3.85 ppb, 1.04 ppm, 18.0 ppb, and 49.5 ppb, respectively, and on February 8, they were 109 μg m⁻³, 132 μg m⁻³, 2.45 ppb, 0.80 ppm, 23.9 ppb, and 24.7 ppb, respectively. The indicative air pollutant on all five days was PM_{2.5}.

The highest AQIs in February 2019 in Chengdu were 137, 120, 122, 108, and 105 on February 5, February 22, February 6, February 23 and February 2, respectively. On February 5, 2019, the concentrations of PM_{2.5}, PM₁₀, SO₂, CO, NO₂, and O₃ were 104 μg m⁻³, 140 μg m⁻³, 3.50 ppb, 0.72 ppm,

17.5 ppb, and 51.8 ppb, respectively, and on February 2, they were $79 \mu\text{g m}^{-3}$, $98 \mu\text{g m}^{-3}$, 2.10 ppb, 0.80 ppm, 17.5 ppb, and 15.9 ppb respectively. The indicator air pollutant for all five days was $\text{PM}_{2.5}$.

In Chengdu, the highest AQIs in February 2020 were 138, 115, 114, 113, and 110 on February 27, February 13, February 26, February 12, and February 24, respectively. On February 27, 2020, the concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $105 \mu\text{g m}^{-3}$, $125 \mu\text{g m}^{-3}$, 2.10 ppb, 0.80 ppm, 16.6 ppb, and 25.2 ppb, respectively, and on February 24, they were $83 \mu\text{g m}^{-3}$, $108 \mu\text{g m}^{-3}$, 2.45 ppb, 0.64 ppm, 18.5 ppb, and 44.3 ppb, respectively. The indicator air pollutant on all five days was $\text{PM}_{2.5}$.

According to the above data, the average of the 15 days with the highest AQI in February from 2017 to 2019 (the non-epidemic period) in Chengdu was 156, and the corresponding average concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $118.1 \mu\text{g m}^{-3}$, $162 \mu\text{g m}^{-3}$, 4.22 ppb, 0.99 ppm, 27.9 ppb, and 32.3 ppb, respectively. The average of the top five days with the highest AQI in February 2020 (the epidemic prevention and control period) was 118, and the corresponding average concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, NO_2 , and O_3 were $89.2 \mu\text{g m}^{-3}$, $108 \mu\text{g m}^{-3}$, 2.38 ppb, 0.74 ppm, 15.7 ppb, and 40.5 ppb, which were 27.9%, 40.2%, 55.8%, 29.6%, 55.9%, and -22.5% lower than those in the period from 2017–2019, respectively. In Table 6, the average AQI in 2020 was 118, which was 27.6% lower than that in the period from 2017–2019 (AQI = 155.7). Compared with the non-epidemic period, during the epidemic prevention and control period, the air quality was improved significantly.

In the combined results of three cities, during the 5 days with

the highest AQI during the epidemic prevention and control action period (February 2020), the average concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and NO_2 , were $89.4 \mu\text{g m}^{-3}$, $106 \mu\text{g m}^{-3}$, 2.31 ppb, 0.72 ppm, and 12.3 ppb, and which were 17.9%, 30.8%, 83.8%, 19.8%, and 62.1%, lower than those in February 2017–2019, respectively. However, the average O_3 concentration (31.8 ppb) in February 2020 did not show a significant decrease, but rather increased by 6.2%. This decrease in the average concentration of $\text{PM}_{2.5}$, PM_{10} , SO_2 , CO, and NO_2 was attributed to the “lockdown” of the cities during the epidemic prevention and control action period (2020). The O_3 concentration increased because a lower NO_2 concentration hindered the $\text{NO} + \text{O}_3$ reaction and resulted in an accumulation of O_3 in the air.

The Wind Streamline and Wind Speed

During this period, the airflow pathway is usually affected by Siberia High (Siberia Anticyclone). Fig. 6 shows the distribution of monthly average near-surface streamlines in Chongqing Municipality and Sichuan Province (including Chengdu and Luzhou City) from January to March in 2019 and 2020, respectively.

Fig. 7 shows the distribution of the monthly average near-surface wind speed in the same regions. The results indicated that the monthly average wind speed in this region from January to March of 2019 was generally higher than the same period in 2020, and the monthly average wind speed in February 2019 was significantly higher than that in January and March of 2019 (about 0.5 m s^{-1} higher). From January to March of 2020, the monthly average wind speed in March was just slightly higher than that in January and

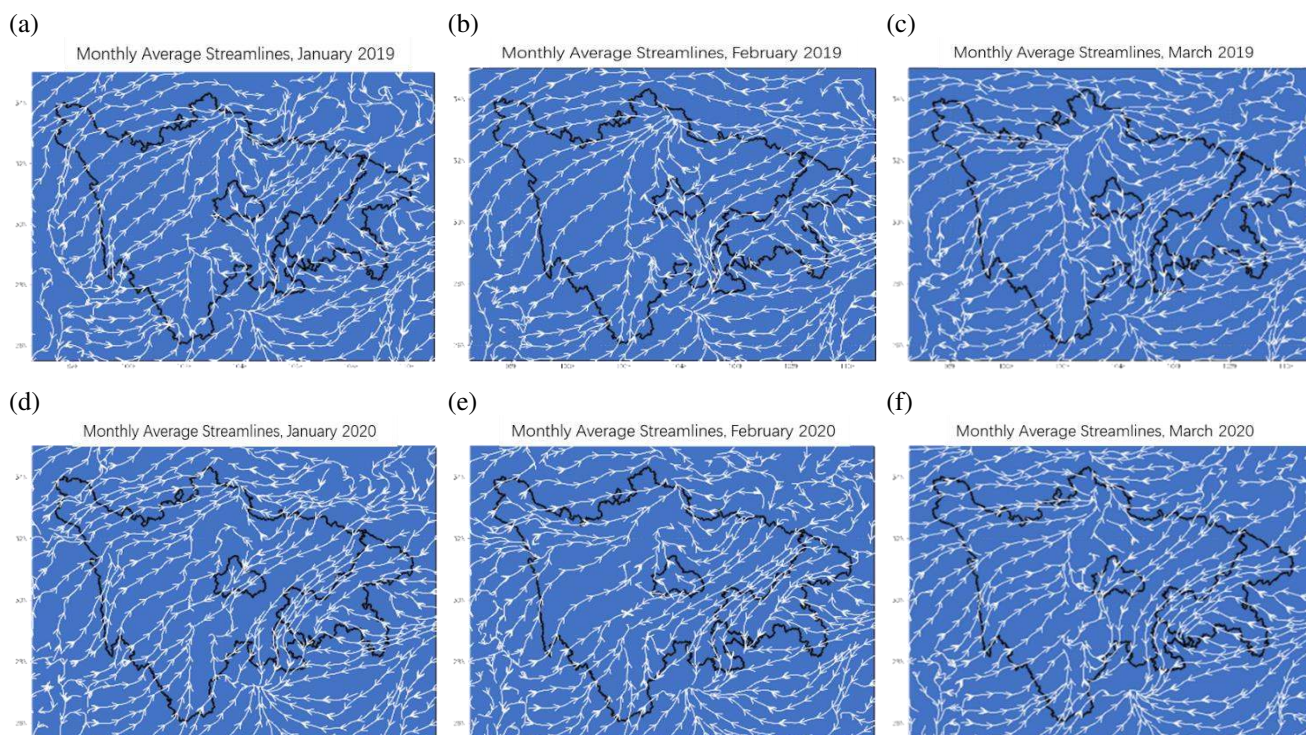


Fig. 6. The wind streamline at Chongqing Municipality and Sichuan Province, China, during January to March in 2019–2020.

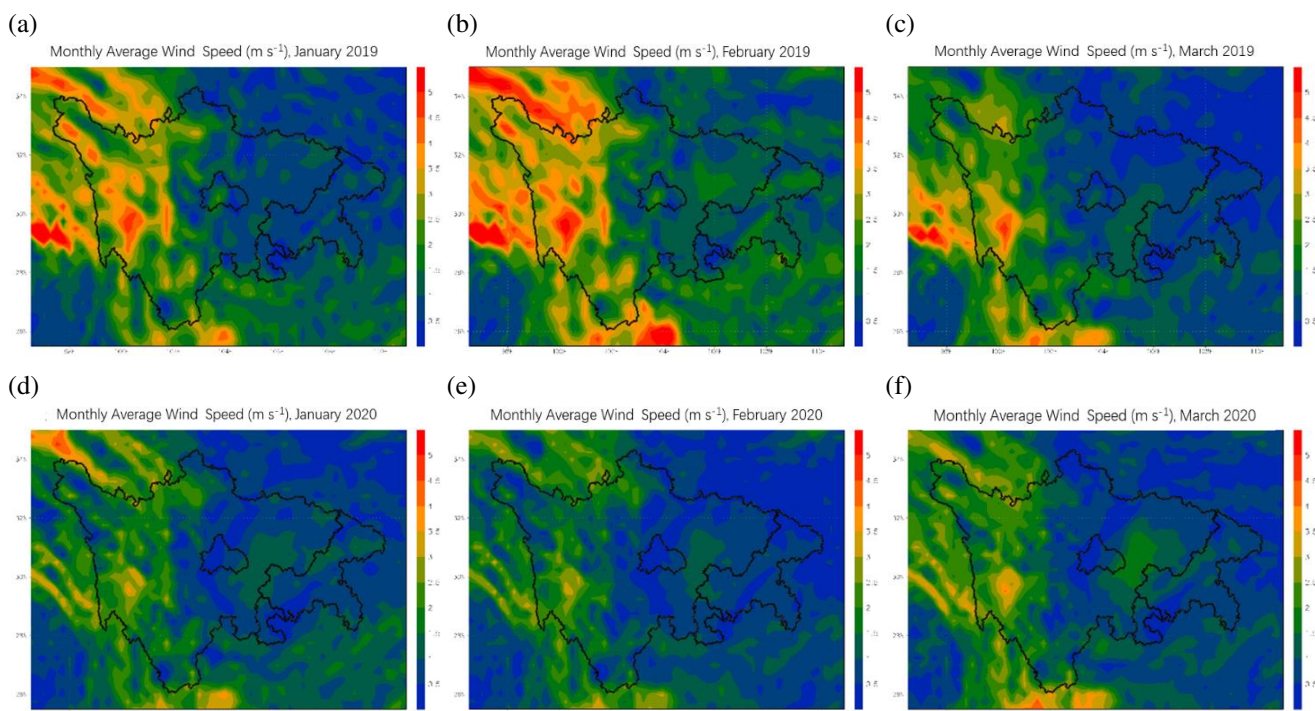


Fig. 7. The wind speed at Chongqing Municipality and Sichuan Province during January to March in 2019–2020.

February of 2020, and the difference between these three months was not obvious. In terms of geographical distribution, Chongqing Municipality is located on the east side of Sichuan province; Luzhou City is located on the southeast corner of Sichuan Province close to the southwest side of Chongqing Municipality, and Chengdu City is located east of the center of Sichuan Province. Due to the influence of the terrain, western Sichuan Province (relatively higher terrain) experiences relatively stronger wind speed compared to Chongqing, Chengdu, and Luzhou (relative lower terrain) in which the monthly average wind speed was below 2.5 m s^{-1} in 2019 and even less than 2.0 m s^{-1} in 2020. According to the distribution of the monthly average streamlines, based on the places where the confluences of streamlines generally have lower wind speed, these three cities are located in lower wind speed regions. In Chongqing, from January to March, the prevailing winds in the southeastern corner are usually southeasterly (SE) to easterly (E) wind, while the prevailing winds in the northern corner (relatively upwind) and southwestern corners (relatively downwind) are usually northeasterly (NE) to east-northeasterly (ENE), and the wind speed is usually lower at the streamline confluence where air pollution is easily accumulated. The prevailing wind in Luzhou from January to March is northerly (N). Luzhou is located downwind of Chongqing, which it means that the air pollutants from Chongqing were easily transported and passes through Luzhou in a northerly to southerly direction with the air flow. Between Chengdu (west side) and Chongqing and Luzhou (east side), there is a banded wind zone with relatively stronger wind speed from January to March, and the wind direction is generally northeasterly to northerly. In Chengdu, the western corner is affected by a relatively stronger wind zone as mentioned above. The prevailing winds

are northeasterly to easterly, so it is not as easy for this banded zone to accumulate air pollutants as it is in the surrounding regions. In other parts of Chengdu, the wind direction is generally more chaotic, resulting in relatively lower wind speed, but it tends toward a northerly wind. Because of this lower wind speed, it is relatively easy for Chengdu to accumulate air pollutants. Generally speaking, because it is affected by Siberia High (Siberia Anticyclone) during the winter, the airflow transport in Chongqing Municipality and the eastern half of Sichuan Province (including Chengdu and Luzhou City) from January to March is dominated by a weaker northeasterly wind (entering from the northeast and leaving from the southwest), and the monthly average wind speed is less than 2.5 m s^{-1} . The wind streamline and wind speed data provide insights into the air transport of pollutants and their effects on the surrounding environment.

CONCLUSIONS

1. In 2017–2019, in Chongqing, the daily AQIs ranged between 27 and 204 and averaged 73.8; in Luzhou, the daily AQIs ranged between 22.7 and 208 and averaged 73.2; while in Chengdu, the daily AQIs ranged between 28.2 and 270 and averaged 85.4. The average AQIs, in order, were Chengdu (85.4) > Chongqing (73.8) > Luzhou (73.2).
2. For the combined AQIs for the three cities, in 2017–2019 in spring, the daily AQIs ranged between 25 and 182 and averaged 72.1; in summer, the daily AQIs ranged between 24 and 206 and averaged 77.5; in autumn, the daily AQIs ranged between 22 and 170 and averaged 61.1, and in winter, the daily AQIs ranged between 28 and 375 and averaged 99.6. The distributions

of the six AQI classes in spring were 3%, 94%, 3%, 0%, 0%, and 0%, respectively; those in summer were 11%, 74%, 15%, 0%, 0%, and 0%, respectively; those in autumn were 29%, 70%, 1%, 0%, 0% and 0%, respectively, and those in winter were 1%, 52%, 44%, 3%, 0%, and 0%, respectively. The average AQI in winter was much higher than in the other seasons. This is because the temperature in winter is low, and the atmospheric temperature inversion phenomenon is prominent, which is not conducive to the dispersion and dilution of pollutants in the air, so the average AQI in winter tends to be higher.

3. In Chongqing, the average AQI values on the highest 5 days were 207, 174, and 179 in 2017, 2018, and 2019, respectively; in Luzhou, they were 240, 174, and 167; in Chengdu, those were 300, 212, and 178, in 2017, 2018, and 2019, respectively. It can be seen that in Chongqing, the air quality was the worst in 2017, followed by 2019, and was the best in 2018; in Luzhou, the air quality was the worst in 2017, followed by 2018, and was the best in 2019; in Chengdu, the air quality was the worst in 2017, followed by 2018, and was the best in 2019. From 2017 to 2019, in general, the air quality improved on an annual basis.
4. For the three cities, the combined AQI in February 2020 was 79.4, which was 23.6% lower than that in the period from 2017–2019 (AQI=101). These results indicated that the prevention and control measures for COVID-19 greatly restricted the movements of people, transportation, engineering construction, industrial production, and commercial trading activity. Therefore, stationary emissions, automobile exhaust, and fugitive emissions were also greatly reduced, so the air quality was significantly improved.
5. The combined results for the three cities on the 5 days with the highest AQIs during the epidemic prevention and control action period (February 2020) reveal, the average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, and NO₂ of 89.4 μg m⁻³, 106 μg m⁻³, 2.31 ppb, 0.72 ppm, and 12.3 ppb, which were 17.9%, 30.8%, 83.8%, 19.8%, and 62.1%, lower than those in February 2017–2019, respectively. However, the average O₃ concentration (31.8 ppb) in February 2020 did not show a significant decrease, but rather increased by 6.2%. The decrease in the average concentrations of PM_{2.5}, PM₁₀, SO₂, CO, and NO₂ was attributed to the “lockdown” of the cities during the epidemic prevention and control action period (February 2020). An increase in the O₃ concentration was because a lower NO₂ concentration hindered the NO + O₃ reaction and resulted in an accumulation of O₃ in the air.
6. In general, due to effects of the Siberia High (Siberia Anticyclone) during winter, the airflow transport features in Chongqing Municipality and the eastern half of Sichuan Province (including Chengdu and Luzhou City) from January to March was dominated by a weaker northeasterly wind (entering from the northeast and leaving from the southwest), and the monthly average wind speed was below 2.5 m s⁻¹. The wind streamline

and wind speed data provides insights into the air transport of pollutants and their effects on the air quality in the surrounding environment.

7. This study provides useful information for the development of air pollution control strategies and adds to the body of research on this topic in the literature.

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Received for review, June 8, 2020

Revised, June 18, 2020

Accepted, June 22, 2020