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Particle composition, sources and evolution during the COVID-19 lockdown period in Chengdu, southwest China: Insights from single particle aerosol mass spectrometer data

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HIGHLIGHTS
• Single aerosol particles during the COVID-19 lockdown were measured based on SPAMS.
• The lockdown caused reductions in PM$_{2.5}$, NO, NO$_2$, SO$_2$ and CO, while increase in O$_3$.
• Vehicle emission particles decreased the most (by 14.9%) during lockdown period.
• Pollution formation mechanism before and during lockdown was completely different.

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ABSTRACT
In order to investigate the effects of the Coronavirus Disease 2019 (COVID-19) lockdown on air quality in cities in southwest China, a single particle aerosol mass spectrometer (SPAMS) and other online equipments were used to measure the air pollution in Chengdu, one of the megacities in this area, before and during the lockdown period. It was found that the concentrations of fine particulate matter (PM$_{2.5}$), nitric oxide (NO), nitrogen dioxide (NO$_2$), sulfur dioxide (SO$_2$) and carbon monoxide (CO) decreased by 38.6%, 77.5%, 47.0%, 35.1% and 14.1%, respectively, while the concentration of ozone (O$_3$) increased by 57.5% from the time before to the time during lockdown. All particles collected during the study period could be divided into eight categories: biomass burning (BB), coal combustion (CC), vehicle emissions (VE), cooking emissions (CE), Dust, K-nitrate (K$\text{--NO}_3$), K-sulfate (K$\text{--SO}_4$) and K-sulfate-nitrate (K-SN) particles, and their contributions changed significantly after the beginning of lockdown. Compared to before lockdown, the contribution of VE particles experienced the largest reduction (by 14.9%), whereas the contributions of BB and CE particles increased by 7.0% and 7.3%, respectively, during the lockdown period. Regional transmission was critical for pollution formation before lockdown, whereas the pollution that occurred during the lockdown period was caused mainly by locally emitted particles (such as VE, CE and BB particles). Weighted potential source contribution function (WPSCF) analysis further verified and emphasized the difference in the contribution of regional transmission for pollution formation before and during lockdown. In addition, the potential source area and intensity of the particles emitted from different sources or formation mechanisms were quite different.

1. Introduction

At the end of 2019, there was a sudden outbreak of the Coronavirus Disease 2019 (COVID-19) in China, which, as it did across most of the globe, went on to reach pandemic level, posing serious threats to public life and health. In order to prevent the spread of COVID-19, a first-level public health emergency response (ELPHER) was triggered throughout China in January 2020. During the ELPHER period, except for some mainstay sectors that maintained the operation of ordinary human life and society, most sectors, including traffic, construction, commerce,
catering, tourism and industrial activities, were subjected to an extreme or complete standstill (Huang et al., 2020; Sun et al., 2020; Li et al., 2020; Zheng et al., 2020). Therefore, the ELPHER period is also called the “COVID-19 lockdown” period. Since various types of anthropogenic sources are important contributors to air pollutants, especially in urban areas, all control measures during the lockdown period not only effectively limited the spread of the epidemic, but also made great changes in the emissions of air pollutants from anthropogenic sources. Therefore, this lockdown provides a unique opportunity to investigate the response of air pollution sources to air pollution in this area.

2. Material and methods

2.1. Sampling site and instruments

The measurement period ran from January 15 to February 14, 2020. The observation site was located on the roof (25 m above ground level) of the School of Civil Engineering, Southwest Jiaotong University (30.70° N, 104.06° E). The building is located near the North Second Ring Road, which is surrounded by roads, schools, shopping malls, restaurants and residential areas, and therefore reflects the typical atmospheric conditions in urban Chengdu. According to the implementation of the lockdown, the whole measurement period can be further divided into before (January 15 to 24) and during (January 25 to February 14) the lockdown period (see Fig. 1).

The SPAMS instrument employed in this study, developed by Hexin Analytical Instrument Co. Ltd (Guangzhou, China) and described in detail by Li et al. (2011), was used to measure the size and mass spectral information of single aerosol particles with a vacuum aerodynamic diameter ranging from 0.2 to 2.0 μm. Meanwhile, gaseous pollutants, including CO, SO2, nitrogen oxides (NOx = NO + NO2) and O3 were measured with CO12M, AF22M, AC32M and O342M analyzers (Environ Tech, China) (Zhang et al., 2017, 2018). The SPAMS instrument employed in this study, developed by Hexin Analytical Instrument Co. Ltd (Guangzhou, China) and described in detail by Li et al. (2011), was used to measure the size and mass spectral information of single aerosol particles with a vacuum aerodynamic diameter ranging from 0.2 to 2.0 μm. Meanwhile, gaseous pollutants, including CO, SO2, nitrogen oxides (NOx = NO + NO2) and O3 were measured with CO12M, AF22M, AC32M and O342M analyzers (Environ Tech, China) (Zhang et al., 2017, 2018).

Fig. 1. Time series of meteorological parameters and concentrations of gaseous pollutants, PM2.5 and PM10 during the study period (the gray background indicates the period before lockdown, while the rest is the COVID-19 lockdown period).
2.2. Data analysis

2.2.1. SPAMS data analysis

The particle size and chemical composition were obtained via SPAMS mass spectral analysis using the Computational Continuation Core (version 3.0) toolkit in MATLAB 7.1.2 (Math Works Inc., Natick, MA, USA). The mass spectral data were grouped into different clusters using an adaptive resonance theory neural network algorithm (ART-2a) with a vigilance factor of 0.6 and a learning rate of 0.05 over 20 iterations (Hopke and Song, 1997; Song and Hopke, 1999). Then, the first 158 clusters generated by ART-2a (representing more than 96% of all the analyzed particles) were further manually merged into eight particle types based on the similarity of chemical features and temporal variations. Each particle type was named by its chemical composition, but the name does not represent all chemical species in the single particle mass spectra.

2.2.2. Weighted potential source contribution function

The potential source contribution function (PSCF) is an effective method for identifying a regional source on the basis of the HYSPLET (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler et al., 2009; Liu et al., 2020; Wang et al., 2009). The conditional probability function of the pollution contribution of each grid to the affected area was indicated by calculating the ratio of pollution trajectory passing through this grid, and \( n_i \) is the number of all trajectories passing through this grid, and \( m_n \) is the number of pollution trajectories (Polissar et al., 1999). The corresponding PSCF calculation formula is:

\[
PSCF_{ij} = \frac{m_{ij}}{n_i}
\]

In this study, the PSCF grid covered a domain over the range of 27°–34° N and 100°–110° E with 0.1° × 0.1° resolution. It is worth noting that cells with few endpoints can lead to a high degree of uncertainty in the PSCF method, and so an arbitrary weight function \( W_i \) was multiplied into the PSCF values to better reflect the uncertainty in the values for these cells (Wang et al., 2015b). Then, the calculation formula could be written as:

\[
W_{ij} = \begin{cases} 
1.00 & n_0 > 3n_{ave} \\
0.70 & 1.5n_{ave} < n_0 \leq 3n_{ave} \\
0.40 & n_{ave} < n_0 \leq 1.5n_{ave} \\
0.17 & n_0 \leq n_{ave}
\end{cases}
\]

in which \( n_{ave} \) is the average number of trajectory endpoints of each grid.

3. Results and discussion

3.1. Pollution characteristics before and during the lockdown period

As shown in Fig. 1, the meteorological parameters in the two periods were similar, with average temperatures of 9.0 ± 1.7 °C and 10.1 ± 2.7 °C, and relative humidities of 70.1 ± 13.9% and 69.0 ± 13.0% before and during the lockdown period, respectively. Meanwhile, the meteorological conditions were stable and the wind speed was low, with mean values of 1.5 ± 1.0 m s\(^{-1}\) and 1.5 ± 0.9 m s\(^{-1}\), respectively, in the two periods.

Unlike the meteorological parameters, gaseous pollutants experienced significant changes during the lockdown period. NO, which is mainly emitted from vehicles in cities (Dumka et al., 2019), experienced the largest reduction (77.5%). The reduction in NO\(_2\), the oxidation product of NO, reached 47.0%. The reduction in the SO\(_2\) concentration (35.1%) was lower than that of NO and NO\(_2\), which may have been because some coal-fired industries (such as coal-fired power plants) were still needed for normal life, and continued to operate during the lockdown period. The pollutant from incomplete combustion processes, i.e. CO, decreased by only 14.1%, which was a much lower reduction than that of other gaseous pollutants. This is because biomass burning, one important source of CO in Sichuan province, even increased around Chengdu during the lockdown period (see section 3.2). O\(_3\) was the only gaseous pollutant that increased during the lockdown period, with an increase of 57.5%. This is consistent with the results reported in other cities around the world, such as the increases of 57.7% in Barcelona (Tobias et al., 2020), 36.0% in Wuhan (Sicard et al., 2020) and 53.1% in Shanghai (Liu et al., 2021), which can be attributed to there being less NO to react with O\(_3\), as well as less heterogeneous HO\(_2\) (hydroperoxy) radical loss and higher actinic flux with lower particle concentrations (Chu et al., 2021; Wu et al., 2021; Zhang et al., 2020).

It was found that the average mass concentration of PM\(_{2.5}\) was significantly reduced by 38.6% from the period before (75.9 ± 27.5 μg m\(^{-3}\)) to the period during (46.6 ± 20.9 μg m\(^{-3}\)) lockdown due to the control over and reduction in emissions from various anthropogenic sources, and similar reductions were also observed in Beijing (20.0%) (Wang et al., 2020a) and Hangzhou (50.0%) (Liu et al., 2021). Meanwhile, the average mass concentrations of PM\(_{10}\) were also reduced, from 92.4 ± 31.8 μg m\(^{-3}\) to 52.8 ± 24.2 μg m\(^{-3}\), and accordingly there was an obvious improvement in visibility from 6.9 ± 3.9 km to 10.8 ± 4.4 km. The ratio of PM\(_{2.5}\) to PM\(_{10}\) has been used to evaluate the relative contributions of fine/coarse particles to air pollution. In this study, compared to the period before lockdown (0.82), the PM\(_{2.5}\)/PM\(_{10}\) ratio increased to 0.88 during the lockdown period, which means that the contribution of fine particles to total particles increased in Chengdu during the lockdown period. This can be attributed to the combined effect of the Chinese New Year and the strict epidemic controls imposed during the lockdown period, when all kinds of construction activities in the city stopped completely and road dust caused by vehicles was also significantly reduced due to citizens being restricted from going out.

It can be seen from the above analysis that various control measures during the COVID-19 lockdown period effectively reduced most pollutants and improved air quality and visibility in Chengdu. However, the average mass concentration of PM\(_{2.5}\) (46.6 ± 20.9 μg m\(^{-3}\)) was still higher than the national standard (35 μg m\(^{-3}\)) and the O\(_3\) concentration rebounded significantly during the lockdown period. Therefore, the control of air pollution in Chengdu is still facing great challenges, even if anthropogenic sources can be greatly reduced.

3.2. Single particle classification and compositions

Through Art-2a and manual merging, all single particles collected during the entire study periods could be divided into eight categories: biomass burning (BB), coal combustion (CC), vehicle emissions (VE), cooking emissions (CE), Dust, and three kinds of secondary inorganic particles (K-nitrate (K-\(\text{NO}_3\)), K-sulfate (K-\(\text{SO}_4\)) and K-sulfate-nitrate (K-\(\text{SN}\))). Fig. 2 shows the average positive and negative mass spectra of these types of particles.

3.2.1. Biomass burning (BB) particles

Most previous studies have pointed out that 39[K]\(^{+}\) is a critical tracer for biomass burning source (Wang et al., 2015a; Zheng et al., 2020). Meanwhile, a strong −26(CN)\(^{−}\) peak in the mass spectrum of BB particles was found in the study by Chen et al. (2017). Therefore, the first kind of particle was identified as BB particles due to the intense peaks of K-nitrate (K-3\(\text{NO}_3\)), K-sulfate (K-3\(\text{SO}_4\)) and K-sulfate-nitrate (K-3\(\text{SN}\)) in the negative mass spectrum were high, suggesting that this type of particle had undergone a significant aging process (Bi et al., 2011). BB particles accounted for 8.8% of total particles over the whole study period and their contribution
Fig. 2. Average mass spectra of different types of particles.
increased from 5.1% to 12.1% from the period before to the period during lockdown (Fig. 3). In general, there is no biomass burning in the urban area and the BB particles in Chengdu come mainly from the rural areas around the city. In this study, the lockdown period included the Chinese New Year holidays, so the return of large numbers of people to rural areas is likely to have led to an increase in BB particles. At the same time, the control of other particle sources during the lockdown period led to a further increase in the relative contribution of this type of particle.

3.2.2. Coal combustion (CC) particles

Coal combustion has been considered an important source of metal elements [such as copper (Cu), iron (Fe) and lead (Pb)] in the atmosphere. Meanwhile, organic matter (OM) and elemental carbon (EC) are important products of coal combustion. Accordingly, the mass spectrum of CC particles in this study included metal element (such as 56[Fe]⁺ and 206/207/208[Pb]³) and OM (38[C₆H₄]⁻, 43[C₂H₂O]⁻) peaks in the positive mass spectrum and EC (−24[C₂]⁻, −36[C₁₆]⁻ and −56[Cu]⁻) peaks in the negative mass spectrum. The strong peaks of secondary inorganic species, such as −46[NO₃]⁻, −62[NO₃]⁻ and −97[HSO₄]⁻, suggest that this type of particle experienced long-distance transport. This is consistent with the fact that industries that use coal in large quantities are usually located in the areas surrounding Chengdu and other industrial cities. As shown in Fig. 3, the contribution of CC particles decreased by only 1.9% from the period before to the period during lockdown, which is far lower than the decrease in VE particles (14.9%). Consistent with the characteristics of CC particles in previous studies (Luo et al., 2019), OM (40[Ca]) in Chengdu (Luo et al., 2019) and Beijing (Liu et al., 2016). Compared to the period before lockdown, the contribution of CC particles decreased by 2.5% during the lockdown period, which is consistent with the fact that construction activities in the city stopped completely and road dust was reduced during this period.

3.2.3. Vehicle emissions (VE) particles

Consistent with the characteristics of VE particles in previous studies (Xia and Gao, 2011; Yao et al., 2016), the mass spectrum of VE particles in this study contained high loadings of OM (41[C₆H₄]⁻, 43[C₂H₂O]⁻) and EC (24[C₂]⁻, 36[C₆]⁻, 48[C₈]⁻ and 60[C₉]⁻) ions. Most source apportionment studies have pointed out that vehicle emissions are a major source of fine particles in China, especially in urban areas, where the number of vehicles is growing rapidly (Liu et al., 2018; Peng et al., 2016). In this study, VE particles accounted for 20.1% of the total number of particles over the whole study period. Compared with the period before lockdown (27.6%), the proportion of VE particles decreased by 14.9% during the lockdown period (12.7%). This is consistent with the fact that people were restricted from going out and the number of vehicles on the road decreased significantly during the lockdown period.

3.2.4. Cooking emissions (CE) particles

Cooking emissions are an important source of primary organic aerosols in urban regions (Crippa et al., 2013). For example, Zhang et al. (2016) found that cooking emissions organic aerosol accounted for 23% of all organic aerosols in autumn in Beijing, and their contribution increased further when other sources were limited. In this study, the positive mass spectrum of CE particles contained OM ions, such as 41[C₂H₃]⁻ and 55[C₆H₇]⁻. Meanwhile, peaks at −255[C₆H₄O₂] (palmitic acid)⁻ and −281[C₂H₂O₂ (oleic acid)]⁻, reported by Wang et al. (2020b) to be tracers of cooking emission sources, could clearly be found in the negative spectrum. During the entire study period, CE particles accounted for 10.7% of total particles. From the period before to the period during lockdown, their contribution increased significantly from 7.3% to 14.6%. This is because, before lockdown, a large number of people—especially office workers—would choose to eat together in restaurants. According to China’s requirements for the management of pollutant emissions in catering enterprises, most enterprises have installed cooking emission fume filtering systems, so cooking emission pollutants have been reduced effectively. However, during the lockdown period, all restaurants were closed and citizens were restricted from going out. Thus, almost all citizens had to choose family meals at home, and the pollutants emitted from this increased level of home cooking were discharged into the atmosphere with almost no treatment measures, which led to a significant increase in the emissions of CE particles during the lockdown period.

3.2.5. Dust particles

The average mass spectra of Dust particles in this study were characterized by intense ion peaks of soil dust tracer, i.e., 40[Ca]⁺ (Luo et al., 2019). Meanwhile, there were obvious contributions from nitrate ions, such as −46[NO₃]⁻ and −62[NO₃]⁻ in the negative spectrum. This mass spectrum is consistent with those previously reported for Dust particles in Chengdu (Luo et al., 2019) and Beijing (Liu et al., 2016). Compared to the period before lockdown, the contribution of Dust particles decreased by 2.5% during the lockdown period, which is consistent with the fact that construction activities in the city stopped completely and road dust was reduced during this period.

3.2.6. Secondary inorganic particles

There were three types of secondary inorganic particles in this study. As shown in Fig. 2, their positive mass spectra were similar, i.e., dominated by 39[K]⁺. The differences mainly appeared in the negative mass spectra. The ions in the negative mass spectra of K-NO₃ and K-SO₄ particles were dominated by nitrate (−46[NO₃]⁻, −62[NO₃]⁻) and sulfate (−97[HSO₄]⁻) ions, respectively. Meanwhile, the nitrate (−46[NO₂]⁻, −62[NO₃]⁻) and sulfate (−97[HSO₄]⁻) ions dominated the negative mass spectrum of K-SN particles (Xu et al., 2018a; Yang et al., 2017; Zheng et al., 2020). These three types of particles have also been found in summer (Zhang et al., 2017) and autumn (Zhang et al., 2018) in Chengdu and in winter in Xi’an (Li et al., 2019).

Over the whole study period, K-NO₃, K-SO₄ and K-SN particles constituted 21.7%, 3.5% and 23.8% of total analyzed particles, respectively. It is well known that nitrate and sulfate in atmospheric particles are produced mainly by the homogeneous and heterogeneous reactions of their gaseous precursors (NO₂ and SO₂) (He et al., 2014). Meanwhile, the three types of secondary inorganic particles are the products of nitrate and sulfate mixed with other types of particles in the atmosphere. Therefore, the low contribution of K-SO₄ particles may have been determined by the low level of SO₂ (4.5 ± 5.6 μg m⁻³) in Chengdu. In contrast, the high contribution of K-NO₃ particles is consistent with the high level of NO₂ over recent years, which is mainly related to the increasing number of vehicles. According to the China Mobile Source Environmental Management Annual Report (2020), the number of vehicle in Chengdu, the second largest city in China after Beijing, reached 5.2 million. From the period before to the period during lockdown, the contribution of K-NO₃ decreased by 3.2%, which is related mainly to the significant reduction in the number of vehicles on the road during the lockdown period. In contrast, for the two types of sulfate-containing particles, K-SO₄ and K-SN particles, their

Fig. 3. Comparison of the contributions of various particles before and during the lockdown period.
contributions increased by 2.7% and 5.4%, respectively. This may have been due to the lower reduction in SO$_2$ (compared with NO$_x$) during the lockdown period. At the same time, the increase in O$_3$ was more conducive to the homogeneous formation of sulfate.

### 3.3. Particle compositions in different pollution episodes

It can be seen from Fig. 1 that, before the COVID-19 lockdown, the mass concentration of PM$_{2.5}$ was at a high level, and two obvious pollution episodes occurred on January 17–18 and 20–23. The average concentrations of PM$_{2.5}$ in the two episodes reached $68.3 \pm 7.4 \mu g \cdot m^{-3}$ and $102.3 \pm 12.9 \mu g \cdot m^{-3}$, respectively. After the beginning of lockdown, the concentration of PM$_{2.5}$ decreased significantly, but there were three obvious pollution episodes in early February (5, 7–8 and 12–14), and the average concentrations of PM$_{2.5}$ were $59.4 \pm 20.4 \mu g \cdot m^{-3}$, $43.9 \pm 2.5 \mu g \cdot m^{-3}$ and $83.9 \pm 13.9 \mu g \cdot m^{-3}$, respectively. Because anthropogenic sources have been the focus of all kinds of pollution reduction measures in the past few years in China, the pollution characteristics during the lockdown period might just reflect the scenario where some important anthropogenic sources underwent substantial emission reductions. Thus, a study of the pollution episode during the lockdown period could reflect the pollution characteristics that we may face in the future. This could provide a reference for future pollution reduction and treatment. Therefore, in this section we compared the characteristics of a typical pollution episode occurring before (January 20–23, EP1) and during (February 12–14, EP2) the lockdown period, and the average composition throughout the study period.

As shown in Fig. 4, there were obvious differences in the compositions of particles in the three periods. Compared to the whole study period, the total contributions of the three kinds of secondary inorganic particles (i.e., K–NO$_3$, K–SO$_4$ and K–SN particles) all increased during EP1 and their total contribution increased from 49.0% to 60.7%. According to previous studies, secondary inorganic particles experience long-term aging in the atmosphere, and regional transmission makes an important contribution to the increase in the contribution of these particles in Chengdu (Huang et al., 2018; Luo et al., 2020; Wu et al., 2019). Meanwhile, the contribution of CC particles, which are transmitted mainly from the industrial areas around Chengdu or other industrial cities in Sichuan province, increased by 1.4%. In contrast, the contributions of particles that come mainly from local emissions, such as VE and CE particles, all decreased. This suggests that the pollution episode that occurred before lockdown was caused mainly by regional transmission. This is consistent with the formation of a typical pollution process reported in a previous study in Chengdu (Zhang et al., 2021).

Compared with the whole study period, the trend in the change in secondary inorganic particles in EP2 was completely opposite to that in EP1, and their total contribution decreased by 8.1%. In particular, the contribution of K–NO$_3$ particles decreased by 5.3%. However, the contributions of BB particles from rural areas around Chengdu and CE particles from Chengdu city increased by 7.2% and 5.7%, respectively. Meanwhile, we found that, although the contribution of VE particles (16.1%) during EP2 was lower than the average contribution over the whole study period (20.1%), it was 3.4% higher than the average contribution during the lockdown period (12.7%). Therefore, VE particles also made an important contribution to the formation of EP2. Thus, we can conclude that EP2 was caused mainly by biomass burning around Chengdu and local emissions (such as cooking and vehicle emissions) in Chengdu.

### 3.4. Weighted potential source contribution function (WPSCF) analysis

In order to explore the differences in potential source areas of air pollutants in Chengdu before and during COVID-19 lockdown in Chengdu, the WPSCF was used to simulate the source probability distribution of PM$_{2.5}$ and some single particle types in different periods. Here, in addition to the two pollution episodes occurring before and during the lockdown periods (i.e., EP1 and EP2), one period with a low PM$_{2.5}$ mass concentration (January 31 to February 3, when the average concentration was 34.6 $\pm$ 4.4 $\mu g \cdot m^{-3}$, referred to as the “clean period”) was also selected for a comparison of potential source areas. Meanwhile, in addition to the PM$_{2.5}$ mass concentration and total particle number concentration (“Total”), one typical regional transmission particle type (i.e., K–SO$_4$ particles) and one typical local emitted particle type (i.e., VE particles) were selected for the WPSCF analysis, so as to obtain more comprehensive results for potential source differences.

As shown in Fig. 5, the potential source areas of various pollutants (PM$_{2.5}$, “Total”, K–SO$_4$ and VE particles) in the three periods (clean, EP1 and EP2) had obvious differences. During the clean period, the potential sources of PM$_{2.5}$ were distributed mainly in the area to the east of Chengdu, and the corresponding WPSCF value was low (<0.5), which means that the contribution of regional transmission to PM$_{2.5}$ in Chengdu was low during this period, and PM$_{2.5}$ in Chengdu came mainly from local emissions. There was good consistency in the potential source areas of “Total” and K–SO$_4$ particles, which were concentrated mainly in the areas to the east and south of Chengdu. Although the potential source area in the south was much smaller than that in the easterly direction, the WPSCF value was much higher than that in the eastern area. Meanwhile, the potential source area in the eastern area for “Total” and K–SO$_4$ particles was larger than that in the eastern area for PM$_{2.5}$. Although the potential source areas of VE particles were also located in the areas to the east and south of Chengdu, their potential source areas were significantly smaller than those of the other two types of particles (especially in the easterly direction).

As mentioned above (section 3.3), EP1 was the pollution episode with the highest mean value of PM$_{2.5}$ and it had a long duration during the whole study period. Therefore, it can easily be found that the potential source areas were more complex than in the other two periods, and the areas with high WPSCF values (>0.7) were widely distributed in the areas surrounding Chengdu. As shown in Fig. 5, the areas with high WPSCF values for PM$_{2.5}$ were distributed mainly in the areas surrounding Chengdu and in the areas to the northeast and southeast of Chengdu. At the same time, there were areas with obviously high WPSCF values located in the transition area between Sichuan province and Chongqing. The potential source areas of “Total” particles during EP1 were distributed mainly in the area to the northeast of Chengdu, and the areas with high WPSCF values were close to Chengdu. Similar to
PM$_{2.5}$, the potential source areas of K–SO$_4$ particles were distributed mainly in the areas to the northeast and southeast of Chengdu and the junction area of Sichuan province and Chongqing, showing obvious regional transmission characteristics, but the intensity of its WPSCF was far weaker than for PM$_{2.5}$. The potential source area of VE particles was the smallest of all pollutants, and its high WPSCF values were concentrated mainly in the areas surrounding Chengdu, which is consistent with the fact that this type of particle comes mainly from vehicle emissions in Chengdu and surrounding areas. According to previous studies, in the many cities located in the areas to the east and south of Chengdu (such as Deyang, Mianyang, Guangan, Chongqing and Zigong), the pollutants they produced will cause the formation of pollution in Chengdu through air mass transport (Li et al., 2017). At the same time, a study by Huang et al. (2019) also found that these areas are important potential sources of PM$_{2.5}$ in Chengdu, which is consistent with the results of potential source analysis during EP1 in this study.

Unlike the two periods before the COVID-19 lockdown, during EP2 the area to the east of Chengdu contributed little to pollution, and its potential source areas were distributed mainly in the area to the west of Chengdu. Except for PM$_{2.5}$, the WPSCF values of the potential source areas of other pollutants were at a low level. This means that the pollution episode occurring during the lockdown period was caused mainly by local emissions in Chengdu.

On the whole, regional transmission contributed significantly to the pollution episode before lockdown and the potential source areas were distributed mainly in areas to the northeast and/or southeast of Chengdu. Whereas, during the clean period, the high WPSCF values were concentrated mainly in the area to the south of Chengdu. However, great changes took place during the lockdown period, and the potential source areas during EP2 were distributed mainly in the area to the west of Chengdu and the WPSCF intensity was far lower than during EP1, which means that the pollution episode during the lockdown period was caused mainly by local emissions. This is consistent with the formation mechanisms of the two pollution episodes we analyzed in section 3.3. On the other hand, although the directions of the potential source areas of different pollutants in the same period were similar, the intensity of their WPSCF values was different due to differences in emission sources or formation mechanisms; for example, the potential source area of K–SO$_4$
particles was much larger than that of VE particles.

4. Conclusions

After the outbreak of COVID-19, a rigorous lockdown was implemented in China in order to prevent its spread. While effectively controlling the spread of the epidemic, the lockdown also significantly affected air quality. In this study, we measured single aerosol particles in Chengdu, one of the megacities in southwest China, before and during the lockdown period and found that the concentrations of most pollutants (PM$_{2.5}$, NO, NO$_2$, SO$_2$ and CO) decreased, except for O$_3$ from the period before to the period during lockdown. All the single particles could be divided into eight categories: BB, CC, VE, CE, Dust, K-NO$_3$, K-SO$_4$ and K-SN particles. Compared to the period before lockdown, the contribution of VE particles experienced the largest reduction (14.9%), whereas the contributions of BB and CE particles increased by 7.0% and 7.3%, respectively, during the lockdown period. A further comparison found that regional transmission played an important role in the formation of pollution before lockdown, while pollution during lockdown was contributed mainly by local emissions, which is consistent with the results from WPSFCF analysis. In addition, although the directions of the potential source areas of different pollutants in the same period were similar, the intensity of their WPSCF values was different due to differences in emission sources or formation mechanisms.

Data availability

The data in this study are available from the authors upon request (ruizhao@swjtu.edu.cn).

Author contributions

J. K. Zhang and R. Zhao designed the research. J. K. Zhang, H. Li, L. Y. Chen and W. Zhang conducted the experiments. J. K. Zhang, H. Li and X. J. Huang analyzed the data. J. K. Zhang, H. Li and R. Zhao wrote the paper. J. K. Zhang and R. Zhao reviewed and commented on the paper.

Declaration of competing interest

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

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