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Elucidating the responses of highly time-resolved PM$_{2.5}$ related elements to extreme emission reductions

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**ARTICLE INFO**

**Keywords:** Trace elements
COVID-19 lockdown
High-frequency response
Source
PMF model

**ABSTRACT**

China’s unprecedented lockdown to contain the spread of the novel coronavirus disease (COVID-19) in early 2020, provided a tragic natural experiment to investigate the responses of atmospheric pollution to emission reduction at regional scale. Primarily driven by primary emissions, particulate trace elements is vitally important due to their disproportionally adverse impacts on human health and ecosystem. Here 14 trace elements in PM$_{2.5}$ were selected for continuous measurement hourly in urban representative site of Shanghai, for three different phases: pre-control period (1-23 January 2020), control period (24 January-10 February 2020; overlapped with Chinese Lunar New Year holiday) and post control period (11-26 February 2020) the city’s lockdown measures. The results show that all meteorological parameters (including temperature, RH, mixing layer height et al.) were generally consistent among different periods. Throughout the study period, the concentrations of most species displayed a “V-shaped” trend, suggesting significant effects by the restriction measures imposed during the lockdown period. While this is not the case for species like K, Cu and Ba, indicating their unusual origins. As a case study, the geographical origins of Cu were explored. Seven major sources, i.e., Vehicle-related emission (including road dust; indicative of Ca, Fe, Ba, Mn, Zn, Cu; accounting for 30.1%), shipping (Ni; 5.0%), coal combustion (As, Pb; 4.2%), Se and Cr industry (24.9%), nonferrous metal smelting (Au, Hg; 7.5%) and fireworks burning (K, Cu, Ba; 28.3%) were successfully pinpointed based on positive matrix factorization (PMF) analysis. Our source apportionment results also highlight fireworks burning was one of the dominant source of trace elements during the Chinese Lunar New Year holiday. It is worth noting that 56% of the total mass vehicular emissions are affiliated with non-exhaust sources (tire wear, brake wear, and road surface abrasion).

**1. Introduction**

Fine particulate matter (PM$_{2.5}$) is noted as one of the major air pollutants in Chinese cities with detrimental impacts on public health among other processes (Huang et al., 2014; Lelieveld et al., 2015). Despite trace elements’ limited contribution to PM$_{2.5}$ mass (typically 4-10%), they could continuously accumulate in the lungs and potentially exert irreversible impacts on human health (Moshenbandi et al., 2018; Huang et al., 2018; Zhou et al., 2018). This is particularly true for heavy metal species. For example, Fe, Cr, Cu and Mn in PM$_{2.5}$ may result in pulmonary and heart diseases (Cakmak et al., 2014; Lu et al., 2008).

As, Cr, Pb and Se are carcinogenic to humans and animals (Hao et al., 2018; Gao et al., 2016). Previous studies have shown that Cr, Fe and V had a variety of oxidation states, which could facilitate or exacerbate several atmospheric redox reactions and catalyze the production of oxidized species (ROS) (Chang et al., 2018; Venter et al., 2017). Furthermore, some trace elements (e.g., Fe, Mn, Cr, V, Ni) can serve as important catalysts to facilitate the formation of sulfate aerosols (Harris, 2013; Cui et al., 2019). As a consequence, it is crucial to study the sources of trace elements and understand their effects on public health.

The 2020 began with stringent regulations and timely interventions from the Chinese Government and other key actors. These measures ranged from road closures, quarantines among other public protocols, aimed at controlling the spread of the coronavirus (COVID-19). Laid down periods, in relation to the Spring Festival holiday was extended from 24 to 31 January to 10 February (Wang et al., 2020a). Measures to
control the epidemic during the Spring Festival seriously affected China’s economic development, which led to a massive decline in energy demand, vehicular and domestic flight operations (Wang et al., 2020b; Cui et al., 2020). During the Spring Festival, domestic flights and other forms of transportation declined by more than 70 percent; energy production in coal-fired power plants decreased by one third whilst production in the steel industry was the lowest in nearly five years (Chang et al., 2020). The social cost of COVID-19 was huge, but served as an avenue or unique opportunity to study the responses of atmospheric pollution to extreme anthropogenic emission reductions.

Some studies reported that air quality in China improved amid the pandemic or lockdown (Xu et al., 2020; Chang et al., 2020; Zhang et al., 2020). Compared with prior to the lockdown, the concentrations of PM$_2.5$, PM$_{10}$, CO$_2$ and NO$_x$ jointly decreased at varying degrees during the lockdown (Li et al., 2020; Cui et al., 2020). However, there were few studies that reported, the changes and sources of trace elements in PM$_{2.5}$ during the control period (Li et al., 2020; Zheng et al., 2020; Cui et al., 2020). Most trace elements were stable after emissions, thus their occurrence in the atmosphere are indicative of specific sources (Chang et al., 2017, 2018). The measurement period spanned from 1 January to February 26, 2020. According to the timing of the COVID-19 lockdown, we divided it into three periods, i.e., before lockdown (1–23 January 2020), during lockdown (24 January-10 February 2020) and after lockdown (11–26 February 2020).

2. Methods

2.1. Sampling site

5 km apart to the urban center (People’s Square), the sampling site was located on the rooftop of an office building in Pudong district of Shanghai (31.233°N, 121.545°E; 15 m a.g.l). Except for road traffic, there were no metal-related strong discharge sources around the site. Also there were no high-rise buildings nearby to hinder the flow of air. Therefore, the sampling location can be considered as an ideal urban receptor site for trace elements emission sources that were well mixed (Chang et al., 2017, 2018). The measurement period spanned from 1 January to February 26, 2020. According to the timing of the COVID-19 lockdown, we divided it into three periods, i.e., before lockdown (1–23 January 2020), during lockdown (24 January-10 February 2020) and after lockdown (11–26 February 2020).

2.2. Instrumentation

Hourly ambient mass concentrations of 14 elements (Fe, K, Ca, Zn, Mn, Pb, Ba, Cu, As, Ni, Cr, Se, Hg and Au) in PM$_{2.5}$ were determined by a Xact multi-metal on-line analyzer (Model Xact™625; Cooper Environmental Services LLT, OR, USA) (Lei et al., 2019; Phillips-Smith et al., 2017). Specifically, the multi-metal online analyzer provides suction through the sampling pump, and the air in the environment is sampled by the PM$_{2.5}$ cutter (Model VS621; BGI Inc, MA, USA) at a flow rate of 16.7 L min$^{-1}$, then the inhaled sample is collected on the filter belt. The PM$_{2.5}$ sediment produced on the filter belt enters the analysis area from the rotating shaft, and the non-destructive X-ray fluorescence (XRF) is used to analyze the content of the sampled metal elements. The metal concentration of the corresponding time period is obtained through data processing. Sampling and analysis were carried out almost continuously at the same time. The analysis can be performed every 15, 30, 60, 180 or 240 min. Built in metal (Cr, Cd, Pb) probe test and automatic operation was conducted once each day. The minimum detection limit for 1 h resolution is as follows (ng m$^{-3}$): Si (17.80), K (1.17), Ca (0.30), V (0.12), Cu (0.27), Zn (0.23), As (0.11), Se (0.14), Mn (0.14), Fe (0.17), Ni (0.10), Ag (1.90), Ba (0.39), Pb (0.13) and Cr (0.12) (Chang et al., 2018).

Ambient temperature (T), relative humidity (RH), wind direction (WD) and wind speed (WS) were provided by the Shanghai Meteorological Bureau.

2.3. Positive matrix factorization (PMF) model for source apportionment

The PMF model is a widely-used and effective source allocation method for solving pollution sources, as well as quantifying the contribution of sources to particulate matter (Wang et al., 2018; Chang et al., 2018; Cui et al., 2019). The principle of the PMF model is embodied in its equations. The matrix equation of PMF is:

$$X_{mn} = \sum_{i=1}^{j} g_{mi} f_{in} + e_{mn}$$

where $X_{mn}$ is the n-th species concentration measured in the m-th sample; $g_{mi}$ is the contribution of the i-th source to the m-th sample, and $f_{in}$ is the concentration of the n-th species in the i-th source. The matrix $e_{mn}$ represents part of the data that cannot be explained in the model. The non-negative terms of $g_{mi}$ and $f_{in}$ use iteration to minimize the objective function $P$:

$$P = \sum_{m=1}^{j} \sum_{n=1}^{i} (e_{mn})^2$$

where $e_{mn}$ are the measurement uncertainties.

In this study, the EPA PMF5.0 model was used to quantify the contributions and sources of trace elements in PM$_{2.5}$. For trace elements, the fractional measurement uncertainty in PMF analysis was set at 10%. The element concentration below the minimum detection limit, we replaced...
Unc = $\sqrt{(\text{Fractional Measurement Uncertainty} \times \text{concentration})^2 + (0.5 \times \text{MDL})^2}$

In this study, the number of factors from 4 to 10 was tested using the PMF model to determine the optimal factor solution. The final selection of seven factors. The average $Q/Q_{\text{exp}}$ ratio in this study was 6.37 (Fig. S1). The final number of factors was determined based on the uncertainty analysis of Bootstrap (BS) and dQ-controlled displacement of factor elements (DISP) methods. Details of the uncertainty analysis are described in the supporting information (Paatero et al., 2014; Brown et al., 2015).

3. Results and discussion

3.1. Mass concentrations

Time series of hourly concentrations of trace elements in Shanghai Pudong determined by the Xact during 1 January to February 26, 2020 are presented in Fig. 1. The average and standard deviation of the mass concentrations of 14 trace elements are arranged in descending order (including the concentration of each element in the before, during and after) are shown in Fig. 2.

The concentration of K (642.2 ± 552.0 ng m$^{-3}$) is the highest in this study, followed by Fe (172.4 ± 152.3 ng m$^{-3}$), Ca (120.1 ± 178.1 ng m$^{-3}$), Zn (60.0 ± 75.8 ng m$^{-3}$), Ba (22.6 ± 26.1 ng m$^{-3}$), Mn (22.0 ± 33.2 ng m$^{-3}$), Pb (20.6 ± 19.3 ng m$^{-3}$), Cu (10.1 ± 8.3 ng m$^{-3}$), As (6.2 ± 5.3 ng m$^{-3}$), Ni (2.9 ± 2.2 ng m$^{-3}$), Au (2.6 ± 2.3 ng m$^{-3}$), Hg (2.2 ± 1.1 ng m$^{-3}$), Se (1.9 ± 1.9 ng m$^{-3}$) and Cr (1.9 ± 2.9 ng m$^{-3}$). Based on the ambient air quality standards of China (GB 3095–2012) and World Health Organization (WHO) ambient air quality standards, the atmospheric concentrations (ng m$^{-3}$) limits of Hg, As, Cr, Mn and Ni are 50 (1000 for WHO), 6 (6.6 for WHO), 0.025 for WHO, 150 for WHO and 20 (25 for WHO). During the control period, the concentration of trace elements in Shanghai is yet to reach China limit. Nevertheless, the concentration of most trace elements in the atmosphere of Shanghai is usually one or two orders of magnitude higher than that of Europe and North America. The concentrations are comparable to those usually measured in highly industrialized areas such as Gwangju (South Korea) (Sofowote et al., 2015; Phillips-Smith et al., 2017; Park et al., 2014). Most analytical techniques only record data on the total metal content, with little information on specific metal compounds or chemical forms. In the absence of such information, it is generally assumed that many elements from human activities (especially from combustion sources) are present in the atmosphere as oxides, so we reconstructed the average mass concentrations of metals and crustal oxides. The calculated mass concentration after reconstruction in this study is 1.64 μg/m$^3$, which is 3.8% of the total mass of PM$_{2.5}$ (43 μg/m$^3$). The calculation of the reconstruction mass is described in detail in other articles (Dabek-Zlotorynska et al., 2011).

3.2. Concentrations of trace elements in the three periods

The concentrations of trace elements may be affected by meteorological factors. To investigate the effect of meteorological conditions on PM$_{2.5}$, we analyzed the correlation between temperature, PBLH and PM$_{2.5}$. As can be seen in figure S3, temperature and PBLH are poorly correlated directly with PM$_{2.5}$. As can be seen in figure S3, S4, temperature and PBLH are poorly correlated directly with PM$_{2.5}$. Therefore, the influence of meteorological conditions on PM$_{2.5}$ was weak. According to Chang et al. (2020), during the 2020 New Year Holidays, wind speed and PM$_{2.5}$ concentration had no correlation. Other meteorologic parameters (e.g., T, RH) were similar to those during the 2019 New Year Holidays. Here, the meteorological factors in this context can be said not to be the main cause of pollution during the 2020 Spring Festival. Conversely, changes in trace elements are mainly influenced by other factors.

As shown in Figs. 1 and 2, the concentrations of Fe, Ca, Zn, Mn, Ni and Cr presented a “V-shaped” trend during the study period. Mn, Cr, Zn, Fe and Ca elements had a large variation in concentration. The concentration of Mn pre-control period was 38.7 ng m$^{-3}$, while experiencing a reduction of 9.6 ng m$^{-3}$ during the control period; with a decrease of 75%, and increased to 12 ng m$^{-3}$ amidst the post-control period (Table 1). Cr dropped from 3.0 ng m$^{-3}$ before the control period to 0.7 ng m$^{-3}$ in the control, with a decrease of 70%, and...
increased to 2.1 ng m\(^{-3}\) post-control period. The concentration of Zn was 96.0 ng m\(^{-3}\) before control, decreased by more than 65% to 33.3 ng m\(^{-3}\) during the control period, and increased to 38.8 ng m\(^{-3}\) after control. Fe dropped from 231.4 ng m\(^{-3}\) pre-control period to 106.3 ng m\(^{-3}\) during the control period, a decrease of 54%, and increased to 162.1 ng m\(^{-3}\) post-control period. The concentration of Ca decreased from 128.0 ng m\(^{-3}\) before the control period to 61.2 ng m\(^{-3}\); it decreased by 52% during the control period, and increased to 174.5 ng m\(^{-3}\) after control. The results presented in this section show the significant effects of the restriction measures imposed during the lockdown. Ni and Hg experienced a slight decline during the COVID-19 lockdown. The change of Au before and during the control period was minimal with an obvious increase amid post-control period.

The concentration of Pb before control was 27.9 ng m\(^{-3}\); however it decreased to 19.6 ng m\(^{-3}\) during the control era, and subsequently settled at 11.5 ng m\(^{-3}\) after the control period. The concentration of As before control was 7.6 ng m\(^{-3}\), dropped to 5.5 ng m\(^{-3}\) during control, and reached 4.2 ng m\(^{-3}\) after the control period. The concentration of Se before the control period was 1.6 ng m\(^{-3}\), and during the control period was decreased to 1.3 ng m\(^{-3}\); after the control period. This shows that Pb, As, and Se were greatly affected by the epidemic, and their concentrations were always declining. The restriction measures imposed during the lockdown had limited impact on K, Cu, and Ba, whilst their concentration levels remained high (Table 1). The changes could be attributed to the fireworks burning during the Spring Festival celebration (Kong et al., 2015).

### 3.3. Case-specific analysis of Cu

The above mentioned results show that the COVID-19 lockdown among other public protocols were effective in reducing the emissions of most of the studied elements, but had no significant effect on K, Ba and specifically in the case of Cu, which had high concentrations before and during the control period. Our research found that although fireworks burning are banned in Shanghai, its Disneyland has a fireworks show every night (Video Link: https://www.youtube.com/watch?v=ub_GPP6x8jXx&ab_channel=17Shenqi). Therefore, we will use the case-special analysis of the high value of Cu to explore and ascertain whether the sources are mainly from external transmissions or local pollution. It can be observed from Fig. 1 That Cu had high values on 7 January and 24 January. From Fig. 3 (a), we can see that the sources of pollutants in Shanghai on 7 January are complex, and about 33% of the pollutants were directly from regional transmissions, which indicate the high concentration of Cu element was affected by external regional transmissions. So, the high concentration of Cu element before the control period may originate from regional transmission and Fireworks burning. During the control period, the concentration of Cu should have reduced due to the strict control of vehicles, but remained high. Especially on the 24th of January. Ascertain reasons for the high concentration compelled as to analyze the 500 m backward trajectory of Shanghai on 24 January. It can be seen from Fig. 3 (b) that the contamination is mainly caused by local sources. We understand that on
that day Shanghai Disneyland held a grand fireworks display. Therefore we observed higher concentrations of Cu on this day. As shown in Figure S5, the high concentration of Cu during the lockdown (after January 24) was mainly caused by regional transport. Due to restrictions on people traveling during the lockdown, the high concentration of Cu during the control period was mainly caused by the burning of fireworks.

### 3.4. Source analysis

In this study, the PMF model was used to analyze 14 measured elements. 5–10 factors were processed for the entire data set, to generate 7 factors as the optimal solution. Seven sources were identified by the PMF model in Fig. 4. The daily changes of the seven sources are presented in Fig. 5. The average concentrations and contributions of the seven sources during the three periods are given in Table 2.

Factor 1 was identified as Vehicle-related emission, due to its high loadings of Mn, Zn, Fe and Cu. From their diurnal variations in Fig. 5, a morning peak and an afternoon peak can be observed, along with working period, indicating these elements are related to vehicles. According to Zhu et al. (2018), in China, more than 10% of Zn and about 55% of Cu emissions emanate from tire wears and brakes. Cu is used as a lubricant and friction material for the brake pedal, while Zn is added to the tire tread to promote the vulcanization process (Lin et al., 2015; Tecer et al., 2012). Fe is the main material of the brake pad, and the brake pedal material also contains Zn and Mn (Zhao et al., 2015). Therefore, the sources of Mn, Zn and Fe are classified as vehicle-related emission. This factor contributed 13.0% (137 ng m\(^{-3}\)) of the total element mass. Further, the concentrations of vehicular emissions were recorded 243, 58, and 72 ng m\(^{-3}\), respectively (Table 2), throughout the study period.

Factor 2 had high loadings of Ni (64%). This element is good indicator of oil combustion. Shanghai has the busiest container port in the world, and about 70% of Ni is emitted from the heavy oil combustion of ship engines (Chang et al., 2018). So, this factor was identified as ship sources. This factor contributed 5.0% (53 ng m\(^{-3}\)) of the total element

| Sources                 | Average | Before | During | After |
|-------------------------|---------|--------|--------|-------|
| Vehicle-related emission| C 137   | 243    | 58     | 72    |
|                         | % 13.0% | 65.1%  | 15.5%  | 19.3% |
| Shipping                | C 53    | 63     | 43     | 51    |
|                         | % 5.0%  | 40.1%  | 27.4%  | 32.5% |
| Coal combustion         | C 45    | 62     | 45     | 21    |
|                         | % 4.2%  | 48.4%  | 35.2%  | 16.4% |
| Se and Cr industry      | C 263   | 357    | 211    | 174   |
|                         | % 24.9% | 48.1%  | 28.4%  | 23.5% |
| Nonferrous metal smelting| C 79    | 70     | 84     | 88    |
|                         | % 7.5%  | 28.9%  | 34.7%  | 36.4% |
| Road dust               | C 181   | 177    | 92     | 286   |
|                         | % 17.1% | 31.9%  | 16.6%  | 51.5% |
| Fireworks burning       | C 299   | 181    | 593    | 136   |
|                         | % 28.3% | 19.9%  | 65.2%  | 14.9% |

Fig. 5. Diurnal variations of the seven sources identified by the PMF model. The error bars represent the 95% confidence intervals of the mean (gray lines).
mass. The concentrations of ship sources before, during and after the control period were 63, 43 and 51 ng m$^{-3}$, respectively.

Factor 3 was linked to coal combustion. It was characterized by high loadings of As (95%) and Pb (38%). In China, 73% of As and 56% of Pb emissions were found to be coal combustion (Tian et al., 2015). Therefore, As and Pb are generally regarded as specific tracers of coal-related emissions (Cui et al., 2019; Chang et al., 2018). Overall, this factor contributed about 4.2% (45 ng m$^{-3}$) of the total element mass. Amid the specified control periods used in the present study, thus, prior to, during, and post-control periods, the concentrations of coal combustion were 62, 45 and 21 ng m$^{-3}$, respectively. Coal combustion decreased during the control period, and shows control measures during the COVID-19 were effective.

Factor 4 was considered as the Se and Cr industry, with high loadings of Se (80%) and Cr (84%). Se powder was used as a decolorizing agent in the glass production process. Glass production is the main source of Se emissions (Zhu et al., 2018). Research shows that Cr is used in electroplating and leather industries. Specific metal processing industries are also related to Cr emissions (Liu et al., 2018; Querol et al., 2007). This factor contributed about 24.9% (263 ng m$^{-3}$) of the total element mass. The contributions of this factor during the three periods were 357, 221 and 174 ng m$^{-3}$, respectively.

Factor 5 was identified as nonferrous metal smelting. The abundant elements found in factor 5 were Au (95%) and Hg (53%). These two trace elements are relatively important elements in non-ferrous ores such as Cu and Zn. During the smelting process, metals such as Au and Hg in non-ferrous metal ore will inevitably evaporate, and released into the air (Wu et al., 2012). The contribution of nonferrous metal smelting was 7.5% (79 ng m$^{-3}$) to the total elemental mass in PM$_{2.5}$. The concentrations of nonferrous metal smelting amid before, during and after control were 70, 84 and 88 ng m$^{-3}$, respectively.

Factor 6 was identified as dust, because its predominant elements were Ca, Fe and Ba, which explained 83%, 28% and 25% of the concentration, respectively. The factor accounted for 17.1% (181 ng m$^{-3}$) of the total element mass in PM$_{2.5}$. Ca can be used as a tracer element for dust. Shanghai is located on the east coast of China, and was rarely subjected to long-distance migration of crustal materials from the wind and dust of northwest China and Desert (Chang et al., 2017; Wang et al., 2017, 2018). So, Ca may have originated from road dust or urban construction sites. Fe and Ba were caused by brake pads and tire wears. Strict measures during the COVID-19 had made Ca, Fe, Ba more likely to emanate from road dust. The concentrations of dust during the three specified period were 177, 92 and 286 ng m$^{-3}$, respectively.

Factor 7 was considered as fireworks burning, due to the high levels of K, Cu and Ba in its composition, representing 45%, 38% and 62% of the concentration, respectively. Some research shows that K, Ba and Cu were reliable tracers for fireworks burning (Liu et al., 2019; Kong et al., 2015). The time series of these elements (Fig. 1.) also show they a higher concentration and presence during the Spring Festival holidays. Although fireworks are banned in Shanghai. However, fireworks are set off nightly at Disneyland. The area was influenced by a continuous local fireworks source with a relatively flat pattern of diurnal variability (Fig. 5.). During the control period fireworks sources were mainly caused by regional transmission. Overall, fireworks burning contributed 299 ng m$^{-3}$ or 28.3% of the PM$_{2.5}$ trace elements. During the three periods, the concentration of the factor were 181, 593, 136 ng m$^{-3}$, respectively.

Considering the scope of this study, in relation to the comparisons outlined above, the vehicular emissions during COVID-19 lockdown decreased by 76%, followed by road dust (48%), Se and Cr industry (38%), ship sources (32%) and coal combustion (27%). Contrarily, the concentrations from fireworks burning and nonferrous metal smelting increased by 228% and 20%, respectively.

4. Conclusion

Hourly concentrations of PM$_{2.5}$ related elements were measured from 1 January to February 26, 2020 in Shanghai. Based on the findings presented above, it can be concluded that:

(1) The concentration of trace element metals in Shanghai is one or two orders of magnitude higher than other countries or cities. This indicates China needs to develop scientific methods, technologies and resources to control trace elements emissions.

(2) Throughout the study period, the concentration of Fe, Ca, Zn, Mn, Ni and Cr showed a V-shaped change, but the fireworks burning during the Chinese Spring Festival (COVID-19 lockdown) had a significant influence on the K, Cu and Ba concentrations.

(3) During the COVID-19 lockdown period, change in the concentration of atmospheric trace elements in Shanghai was mainly controlled by anthropogenic emissions. Trace elements mainly emanate from vehicular emissions, road dust, Se and Cr industry, and fireworks burning. Comparing prior lockdown period, the vehicle-related emissions (mass of elements) during COVID-19 lockdown decreased by 76%. However, the concentrations from fireworks burning dramatically by 228%.

(4) Changes in K, Ba and Cu are unique. Taking Cu as an example, its concentration was affected by external transport and vehicles prior to the lockdown period. However the case during the lockdown period was caused by the fireworks burning. This shows that despite the ban on fireworks burning during the Shanghai festival period, they are still one of the important sources of trace elements.

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.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 41975166), the Jiangsu Natural Science Fund for Excellent Young Scholars (Grant No. BK20211594), the Opening Project of the State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, CAS (Grant No. SKLLOGZR2103), the Opening Project of the State Environmental Protection Key Laboratory of Formation and Prevention of Urban Air Pollution Complex (Shanghai Academy of Environment Sciences, Grant No. CX20200080583), Young Elite Scientist Sponsorship Program by the Jiangsu Provincial Association for Science and Technology, and the Opening Project of Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP$^3$, Grant No. FDLAP19001).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.112624.

References

Brown, S.G., Eberly, S., Paatero, P., Norris, G.A., 2015. Methods for estimating uncertainty in PMF solutions: examples with ambient air and water quality data and guidance on reporting PMF results. Sci. Total Environ. 518–519, 626–635.

Cakmak, S., Dales, R., Kauri, L.M., Mahmud, M., Van Ryswyk, K., Vanos, J., Liu, L., Kumararasan, P., Thomson, E., Vincent, R., 2014. Metal composition of fine particulate air pollution and acute changes in cardiorespiratory physiology. Environ. Pollut. 189, 208–214.

Chang, Y., Deng, C., Cao, F., Cao, C., Zou, Z., Liu, S., Lee, X., Li, J., Zhang, G., Zhang, Y., 2017. Assessment of carbonaceous aerosols in Shanghai, China Part 1: long-term
