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Unbalanced emission reductions and adverse meteorological conditions facilitate the formation of secondary pollutants during the COVID-19 lockdown in Beijing

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HIGHLIGHTS

- Sulfate and nitrate increased during the lockdown, and sulfate contributed more.
- The unbalanced reductions in NOx and VOCs and elevated temperature increased O3.
- The increase in relative humidity facilitated heterogeneous chemistry.
- The elevated photochemistry and heterogeneous chemistry promoted secondary formation.

GRAPHICAL ABSTRACT

ABSTRACT

During the coronavirus disease 2019 (COVID-19) lockdown in 2020, severe haze pollution occurred in the North China Plain despite the significant reduction in anthropogenic emissions, providing a natural experiment to explore the response of haze pollution to the reduction of human activities. Here, we study the characteristics and causes of haze pollution during the COVID-19 outbreak based on comprehensive field measurements in Beijing during January and February 2020. After excluding the Spring Festival period affected by firework activities, we found the ozone concentrations and the proportion of sulfate and nitrate in PM2.5 increased during the COVID-19 lockdown compared with the period before the lockdown, and sulfate played a more important role. Heterogeneous chemistry and photochemistry dominate the formation of sulfate and nitrate during the whole campaign, respectively, and the heterogeneous formation of nitrate at night was enhanced during the lockdown. The coeffects of more reductions in NOx than VOCs, weakened titration of NO, and increased temperature during the lockdown led to the increase in ozone concentrations, thereby promoting atmospheric oxidation capacity and photochemistry. In addition, the increase in relative humidity during the lockdown facilitated heterogeneous chemistry. Our results indicate that unbalanced emission reductions and adverse meteorological conditions induce the formation of secondary pollutants during the COVID-19 lockdown haze, and the formulation of effective coordinated emission-reduction control measures for PM2.5 and ozone pollution is needed in the future, especially the balanced control of NOx and VOCs.

1. Introduction

In the past decades, with the rapid economic development and the acceleration of industrialization and urbanization, China has experienced severe haze pollution with high concentrations of fine particulate matter (PM2.5), posing adverse impacts on the environment and health (An et al., 2019; Huang et al., 2014). Previous studies show that primary emissions, secondary formation, stagnant meteorological conditions, and regional transport are four main factors contributing to the formation of severe haze pollution (An et al., 2019; Sun et al., 2014; Zheng et al., 2015). The formation of haze pollution usually involves a transition from photochemistry

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to aqueous/heterogeneous chemistry (Wang et al., 2016; Zheng et al., 2015). In recent years, the implementation of clean air actions in China has led to a significant reduction in anthropogenic emissions and substantially improved PM$_{2.5}$ air quality (Zhang et al., 2019b), while the responses of particulate matter to changes in precursor concentrations were usually non-linear due to the effects of meteorological conditions and complex atmospheric chemical processes (Li et al., 2019; Li et al., 2020b). Till now, the responses of air quality and atmospheric chemistry to changes in emissions and meteorological conditions remain unclear.

The coronavirus disease 2019 (COVID-19) broke out in December 2019 in Wuhan, China. To control the spread of COVID-19, China has taken a series of control measures to reduce the level of economic and social activities since the lockdown on January 24, 2020, such as the strict control of people flow and traffic. As a result, anthropogenic emissions decreased significantly, especially in transportation (Huang et al., 2020; Wang et al., 2020). The most significant change was the abrupt decline in NO$_2$ concentrations (Liu et al., 2020; Shi and Brasseur, 2020). However, severe haze pollution still occurred in the NCP during the COVID-19 lockdown, accompanied by an increase in ozone concentrations (Huang et al., 2020; Le et al., 2020; Wang et al., 2020). The COVID-19 outbreak provides a natural experiment to explore the response of haze pollution to the reduction of human activities. Recent studies indicated that enhanced formation of secondary air pollutants, adverse meteorology, and regional transport may be the causes of severe haze pollution during the COVID-19 lockdown in the NCP (Huang et al., 2020; Le et al., 2020; Lv et al., 2020; Wang et al., 2020; Xing et al., 2020). The large reductions in NO$_x$ emissions increased ozone and nighttime NO$_x$ radical formation, further increasing the atmospheric oxidation capacity and facilitating the formation of secondary aerosols, and high humidity promoted heterogeneous chemistry (Huang et al., 2020; Le et al., 2020). The formation of secondary organic aerosol (SOA) was enhanced significantly during the lockdown, including less-oxidized oxygenated OA related to aqueous chemistry and more-oxidized oxygenated OA related to both aqueous and photochemical processes (Hu et al., 2021), and the nocturnal chemistry related to NO$_x$ radical may be the additional sources of nighttime SOA (Feng et al., 2022). However, the detailed effects of changes in emissions and meteorological conditions on the atmospheric composition and formation of secondary pollutants during the COVID-19 lockdown remain unclear and need more observation evidence.

In particular, the Spring Festival holiday started on January 24, 2020, and was in the COVID-19 lockdown period. The haze pollution during the Spring Festival is usually affected by fireworks emissions, which contribute a large fraction of PM$_{2.5}$ mass (Ji et al., 2018; Jing et al., 2015). In addition, the additional sources of nighttime SOA (Feng et al., 2022). However, previous studies often overlooked the small reductions in primary aerosol species during the Spring Festival holiday, while the decreases in secondary aerosol species were much smaller (Sun et al., 2020). However, previous studies often overlooked the particularity of the Spring Festival when exploring the characteristics and formation mechanisms of haze pollution during the COVID-19 lockdown.

In this study, we conducted online field measurements on particulate matter, gaseous pollutants, and meteorological parameters during January and February 2020 in Beijing, China, including the periods before the COVID-19 lockdown (January 1 to January 23), during the Spring Festival (January 24 to January 31), and during the COVID-19 lockdown (February 1 to February 29). We studied the characteristics of haze pollution and the formation mechanism of sulfate and nitrate in three periods. Furthermore, we investigated the effects of the changes in emissions and meteorological conditions on secondary formation during the COVID-19 lockdown. Our findings will help to understand the causes of pandemic haze in the NCP and develop more effective control strategies in the future.

2. Methods

2.1. Field measurements

Collocated online gas, particulate, and meteorology measurements were conducted in Beijing from January 1, 2020 to February 29, 2020. The observation site was located on the roof (approximately 20 m above ground) of the School of Economics and Management at Tsinghua University (40.00° N, 116.34° E), a typical urban monitoring site in the northwest of Beijing, as described in previous works (Ma et al., 2020; Xu et al., 2017a; Yang et al., 2020a; Zheng et al., 2015).

The ambient measurement instruments used in this study have been described in previous studies, and data quality assurance/quality control (QA/QC) measures were strictly followed (Duan et al., 2016; Li et al., 2018; Ma et al., 2020; Xu et al., 2017a; Yang et al., 2020a; Zheng et al., 2015). In brief, the mass concentrations of PM$_{2.5}$ were monitored based on the β-ray absorption method using a dichotomous monitor (PM-712, Kimo Electric, Ltd., Japan). The hourly concentrations of sulfate (SO$_4^{2-}$) and nitrate (NO$_3^-$) in PM$_{2.5}$ were measured by a continuous dichotomous aerosol chemical speciation analyzer (ACSA-14; Kimo Electric, Ltd., Japan). The ammonium (NH$_4^+$) concentrations were calculated based on the assumption that they existed in the form of NH$_3$NO$_3$ and (NH$_4$)$_2$SO$_4$ (He et al., 2012). The hourly concentrations of carbonaceous species in PM$_{2.5}$ including organic carbon (OC) and elemental carbon (EC) were monitored with optical transmittance and reflectance method by a particulate carbon analyzer (APC-710; Kimo Electric, Ltd., Japan). We adopted a factor of 1.6 to convert the OC mass into organic matter (OM) mass (Xing et al., 2013; Zhang et al., 2017). The hourly average concentrations of SO$_2$, NO$_2$, NO (NO and NO$_2$), O$_3$, and CO were monitored using the ultraviolet fluorescence method (SA-731; Kimo Electric, Ltd., Japan), chemiluminescence method (NA-721 and NA-722; Kimo Electric, Ltd., Japan), UV absorption method (OA-781; Kimo Electric, Ltd., Japan), and non-dispersive infrared absorption method (CA-752; Kimo Electric, Ltd., Japan), respectively. The hourly concentrations of volatile organic compounds (VOCs) were measured based on the nondispersive infrared (NDIR) method (VOC-770; Kimo Electric, Ltd., Japan). The hourly average meteorological parameters including temperature, relative humidity (RH), wind speed, and wind direction were simultaneously monitored with an automatic meteorological observation instrument (Milos 520, VAISALA Inc., Finland). Besides, hourly concentrations of 23 trace elements in PM$_{2.5}$, including K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Cd, Sn, Sb, Ba, Au, Hg, Tl, and Pb were measured based on the US EPA method IO 3.3 using nondestructive energy-dispersive X-ray fluorescence by an ambient metals monitor (Xact 625, Cooper Environmental Services, Oregon, USA) (Ji et al., 2018; Zhang et al., 2019a).

2.2. Air mass back-trajectory analysis

To explore the influence of regional transport on haze pollution in Beijing, we conducted 48 h air mass back-trajectory analysis using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Model (Stein et al., 2015). The meteorological input was adopted from the National Oceanic and Atmospheric Administration (NOAA) Air Resource Laboratory Archived Global Data Assimilation System (GDAS) ftp://arlftp.arl尚未下载/). The model was run two times per day at starting times of 00:00 and 12:00 LT—local time (16:00 and 4:00 UTC, respectively). The arrival level was set at 500 m above ground level.

3. Results and discussion

3.1. Different pollution characteristics before and during the COVID-19 lockdown

Fig. 1 shows the time series of particulate matter, gaseous pollutants, and meteorological parameters during the COVID-19 outbreak in Beijing. Considering the particularity of the Spring Festival, here we divided the field campaign into three periods: before the COVID-19 lockdown (January 1 to January 23), during the Spring Festival (January 24 to January 31), and during the COVID-19 lockdown (February 1 to February 29), with an average PM$_{2.5}$ concentration of 42.4 (2.1–229.6) μg m$^{-3}$, 110.2 (7.1–366.6) μg m$^{-3}$, and 55.9 (0.3–203.8) μg m$^{-3}$, respectively. The
pollution level and haze episode frequency during the lockdown were higher than those before the lockdown.

The chemical composition of PM$_{2.5}$ exhibited different characteristics among the three periods. We classified the field campaign into clean periods (PM$_{2.5}$ concentration $\leq 75$ μg m$^{-3}$) and polluted periods (PM$_{2.5}$ concentration $> 75$ μg m$^{-3}$), and investigated the evolution of chemical composition in PM$_{2.5}$ with the deterioration of haze during three periods, as shown in Fig. 2. Before the COVID-19 lockdown, the main component of PM$_{2.5}$ was OM, followed by nitrate. From clean periods to polluted periods, the proportion of nitrate increased, whereas the OM proportion decreased, a similar evolution pattern to previous studies in winter in the NCP (Zheng et al., 2015). During the Spring Festival, the main component of PM$_{2.5}$ was OM, followed by nitrate and sulfate. From clean periods to polluted periods, the contribution of sulfate, nitrate, and OM decreased. The high concentrations of potassium (K) and barium (Ba) can explain the missing component of the PM$_{2.5}$ closure during the polluted periods, as shown in Fig. 3, indicating the significant contribution of fireworks (Ji et al., 2018; Jing et al., 2014). As shown in Table S1, the temporal variations of Cr and Ca showed a good correlation with Ba and may also come from fireworks emissions, while other elements (Ca, Mn, Fe, Zn, and Pb) exhibited a weak correlation with Ba and may come from different sources, such as iron/steel plants in the Hebei province and coal combustion in the suburb of Beijing. High concentrations of Ca, Mn, Fe, Zn, and Pb also occurred before and during the COVID-19 lockdown periods, indicating the contribution of regional transport. During the COVID-19 lockdown, the contribution of sulfate and nitrate to PM$_{2.5}$ increased while the ratio of OM decreased compared to the periods before the lockdown. The major component of PM$_{2.5}$ was OM and sulfate during clean and polluted periods, respectively. From clean periods to polluted periods, the proportion of sulfate increased, whereas the proportion of nitrate and OM decreased.

The gaseous pollutants and meteorological conditions also exhibited different characteristics among the three periods. For gaseous pollutants, haze pollution before the COVID-19 lockdown was characterized by relatively high concentrations of primary gaseous pollutants (SO$_2$, NO, CO, and NO$_x$) and low ozone concentrations. In contrast, during the COVID-19 lockdown, the concentrations of primary gaseous pollutants decreased significantly due to the control of human activities, while the ozone concentration increased sharply. Notably, the ratio of NO$_2$ to NO increased dramatically. During the Spring Festival, the SO$_2$ concentrations were relatively high due to the fireworks emissions. As for meteorological conditions, the RH and temperature increased during the COVID-19 lockdown. We conducted air mass back-trajectory analysis during four episodes (EP1–EP4) to investigate the impact of regional transport on meteorological conditions and haze formation, as shown in Fig. S1. During the EP1, i.e., before the COVID-19 lockdown, the air masses came from the northwest at medium speed and brought relatively dry air to Beijing, thus the temperature and RH during EP1 were relatively low. During the EP2, i.e., during the Spring Festival, the air masses came from the north with a...
medium speed at the start and from the surrounding areas of Beijing with extremely low speed during the pollution accumulation periods. During the EP3 and EP4, i.e., during the COVID-19 lockdown, the air masses came from the south at medium speed or from the surrounding areas of Beijing at low speed, one of the most heavily polluted areas in China (An et al., 2019; Zheng et al., 2015), and brought relatively humid air to Beijing, thus the temperature and RH were relatively high. In general, the humid warm air mass from the south through polluted areas aggravated haze pollution, while the dry cold air mass from the north through clean areas favored the scavenging of pollutants.

3.2. Secondary formation mechanism of sulfate and nitrate

Fast production of sulfate and nitrate are key factors driving the formation of haze during the COVID-19 outbreak. To investigate their formation mechanisms, here we used SOR (sulfur oxidation ratio) and NOR (nitrogen oxidation ratio) as indicators of secondary transformation (Zheng et al., 2015), calculated as follows:

\[
\text{SOR} = \frac{n(\text{SO}_2^2)}{n(\text{SO}_4^-) + n(\text{SO}_2)} \\
\text{NOR} = \frac{n(\text{NO}_3^-)}{n(\text{NO}_3^-) + n(\text{NO}_2)},
\]

Fig. 4 shows the correlation between SOR and RH, SOR and ozone concentration, NOR and RH, and NOR and ozone concentration before the COVID-19 lockdown, during the Spring Festival, and during the COVID-19 lockdown. Ozone concentration in the daytime (9:00–17:00) and RH are indicators of photochemistry and heterogeneous chemistry, respectively. SOR exhibited a positive correlation with RH but a weak correlation with ozone in three periods, indicating the importance of heterogeneous reactions to sulfate formation. The distribution of SOR during the COVID-19 lockdown was in the high RH range compared to the other two periods, thereby more conducive to the formation of sulfate. NOR showed an obvious dependence on ozone concentration in the daytime but no apparent correlation with RH in three periods, suggesting the significant contribution of photochemistry to nitrate formation. The distribution of NOR during the Spring Festival and COVID-19 lockdown was in the high ozone concentration range compared to the period before the lockdown, thereby facilitating the formation of nitrate.

Furthermore, we investigated the formation mechanism by analyzing the diurnal variation of sulfate, nitrate, and affecting factors during three different periods, as shown in Fig. 5. Before the COVID-19 lockdown, the diurnal variation of sulfate and nitrate showed a wide peak in the afternoon. The SOR exhibited high values at night, consistent with the diurnal variation of RH, which further indicated that heterogeneous chemistry dominated sulfate formation. The high concentrations of sulfate in the daytime mainly depend on high SO2 concentrations. The NOR exhibited high values...
in the daytime, consistent with the diurnal variation of ozone and temperature, which further indicated that photochemistry dominated nitrate formation. The high concentrations of nitrate in the daytime mainly depend on rapid secondary formation. During the Spring Festival, sulfate showed high concentrations at night, consistent with the diurnal variation of K and Ba concentration (Fig. S2), indicating the influence of fireworks. The SOR exhibited high values at night with high RH, indicating that heterogeneous chemistry at night also contributes to the high sulfate concentrations. Nitrate showed an inapparent variation. The NOR exhibited bimodal patterns: a high peak in the daytime with high values of ozone and temperature, and a weak peak at night consistent with high RH. This indicated that photochemistry in the daytime dominated nitrate formation, and the heterogeneous formation of nitrate at night enhanced it. During the COVID-19 lockdown, the diurnal variation of sulfate showed a bimodal pattern: one peak at noon and another peak at night, corresponding to the peak of SO2 concentration and SOR, respectively. The high sulfate concentration depends on the co-effect of SOR and SO2 concentration. Nitrate also showed a bimodal pattern, consistent with the diurnal variation of NOR. In summary, heterogeneous chemistry and photochemistry are the dominant formation mechanism of sulfate and nitrate during the COVID-19 outbreak, respectively. During the Spring Festival and COVID-19 lockdown, the heterogeneous formation of nitrate at night enhanced compared to the periods before the lockdown.

3.3. Enhanced secondary formation during the COVID-19 lockdown

The enhanced formation of secondary pollutants induced haze pollution during the COVID-19 lockdown, here we studied the effects of the changes in emissions and meteorological conditions on secondary formation. Table 1 compares the differences in characteristics of the typical haze episodes before and during the COVID-19 lockdown. The concentrations of primary pollutants (SO2, NO, CO, and EC) from transportation and industry decreased significantly during the lockdown, consistent with the emission inventory results (Huang et al., 2020). In contrast, the importance of secondary species (NO2/NO ratio, ozone, sulfate, and nitrate) increased during the lockdown. Previous empirical kinetic modeling approach results showed that the ozone formation in Beijing was in the VOC-limited regime (Li et al., 2020a). Therefore, the larger reductions in NOx than VOC during the lockdown promoted the formation of ozone. Besides, the titration effect of NO on ozone can suppress the production of ozone (Shi and Brasseur, 2020; Zhu et al., 2019), thus the extremely low NO concentrations during the lockdown weakened the titration effect and facilitated the formation of ozone. Also, the slight increase in temperature during the lockdown was favorable for ozone formation (Pusede et al., 2015). The recent model simulation results also indicated that the reduction in NOx emissions and changes in meteorological conditions contributed to the increase of ozone during the COVID-19 city lockdown period in the Beijing-Tianjin-Hebei region (Le et al., 2020). The high concentrations of ozone during the lockdown enhanced the atmospheric oxidation capacity and photochemistry. In addition, the high RH during the lockdown periods favored heterogeneous chemistry. As a result, the SOR and NOR increased significantly, leading to an increase in sulfate and nitrate percentage in PM2.5.

3.4. Implications

During the COVID-19 lockdown, the levels of human activities and anthropogenic emissions in China have declined dramatically. Despite the unprecedented strict control measures, severe haze pollution with high ozone levels still occurred in the NCP, as reported in previous papers (Huang et al., 2020). The enhanced formation of secondary pollutants (SO2, NO, CO, and EC) from transportation and industry decreased significantly during the lockdown, consistent with the emission inventory results (Huang et al., 2020). In contrast, the importance of secondary species (NO2/NO ratio, ozone, sulfate, and nitrate) increased during the lockdown. Previous empirical kinetic modeling approach results showed that the ozone formation in Beijing was in the VOC-limited regime (Li et al., 2020a). Therefore, the larger reductions in NOx than VOC during the lockdown promoted the formation of ozone. Besides, the titration effect of NO on ozone can suppress the production of ozone (Shi and Brasseur, 2020; Zhu et al., 2019), thus the extremely low NO concentrations during the lockdown weakened the titration effect and facilitated the formation of ozone. Also, the slight increase in temperature during the lockdown was favorable for ozone formation (Pusede et al., 2015). The recent model simulation results also indicated that the reduction in NOx emissions and changes in meteorological conditions contributed to the increase of ozone during the COVID-19 city lockdown period in the Beijing-Tianjin-Hebei region (Le et al., 2020). The high concentrations of ozone during the lockdown enhanced the atmospheric oxidation capacity and photochemistry. In addition, the high RH during the lockdown periods favored heterogeneous chemistry. As a result, the SOR and NOR increased significantly, leading to an increase in sulfate and nitrate percentage in PM2.5.
Our results provide some insights into the causes of pandemic haze and the development of more effective pollutant control strategies in the future. The short-term strict emission control measures have been widely implemented in major events, such as the 2008 Olympic Games, 2014 Asia-Pacific Economic Cooperation (APEC) summit, 2015 China Victory Day parade (Parade), and 2019 National Day, leading to significant emission reductions (Chu et al., 2018; Li et al., 2016; Wang et al., 2010a; Witte et al., 2009; Yang et al., 2020b). In addition to the emission controls, the meteorological conditions were also important factors affecting air quality (Gao et al., 2011; Wang et al., 2010b). For example, the co-effects of significant emission reductions and favorable meteorological conditions resulted in the occurrence of blue sky days during APEC and Parade (Wang et al., 2017; Xu et al., 2017b). Although the pollutants were reduced significantly during the COVID-19 lockdown, even exceeding the previous largest NO2 reduction during the 2014 APEC Blue, severe haze pollution still occurred in adverse meteorological conditions (Huang et al., 2020; Le et al., 2020; Wang et al., 2020), similar to the situation during the 2019 National Day. This indicates that the emissions in the NCP still exceed the environmental capacity and short-term unfavorable meteorological conditions lead to the formation of haze pollution. Long-term emission reductions are needed to mitigate haze pollution. Our study also indicates that the scientific coordinated pollutant emission control measures are more effective in mitigating air pollution. The
emission reduction strategy formulation of previous major events was based on the scientific simulation, but the COVID-19 outbreak occurred suddenly, and the emission reduction focused on vehicle emissions and interpersonal activities. As a result, the unbalanced reductions in NOx and VOCs led to increased ozone concentration (Huang et al., 2020; Le et al., 2020), thereby facilitating the secondary formation of particulate matter. Therefore, the scientific coordinated emission reduction control measures for PM2.5 and O3 pollution are needed in the future, especially the coordinated control of NOx and VOCs.

4. Conclusions

In this study, we conducted online field measurements of particulate matter, gaseous pollutants, and meteorological parameters in Beijing during January and February 2020, and investigated the characteristics and causes of haze pollution during the COVID-19 outbreak. We divided the field campaign into three periods: before the COVID-19 lockdown, during the Spring Festival, and during the COVID-19 lockdown. Before the COVID-19 lockdown, the haze pollution was characterized by high concentrations of primary gaseous pollutants and low ozone concentrations, while the concentrations of primary gaseous pollutants decreased significantly and ozone concentrations increased sharply during the COVID-19 lockdown. Notably, the ratio of NO2 to NO increased dramatically and the contribution of sulfate and nitrate to PM2.5 increased during the COVID-19 lockdown. Meanwhile, RH and temperature increased. The haze pollution during the Spring Festival was associated with fireworks events, characterized by extremely high concentrations of K and Ba.

Our results show that heterogeneous chemistry and photochemistry were the dominant formation mechanism of sulfate and nitrate during the COVID-19 outbreak, respectively, and the heterogeneous formation of nitrate at night was enhanced during the Spring Festival and COVID-19 lockdown. Despite the dramatic reductions in primary emissions, the unbalanced emission reductions in NOx and VOCs and adverse meteorological conditions (high temperature and RH) during the COVID-19 lockdown led to the increase of ozone concentrations and enhancement of photochemistry and heterogeneous chemistry, thereby facilitating the secondary formation. Our results indicate that the emissions in the NCP still exceed the environmental capacity, thereby short-term unfavorable meteorological conditions induce the formation of pandemic haze, and long-term emission reduction is the driving force for air quality improvement. Furthermore, the formulation of effective coordinated emission-reduction control measures for PM2.5 and ozone pollution is needed in the future, especially the balanced control of NOx and VOCs.

Table 1

| Episode | EP1 | EP2 & EP4 |
|---------|-----|----------|
| PM2.5 (µg m⁻³) | 121.5 | 89.8 |
| SO₂ (µg m⁻³) | 24.6 | 25.2 |
| NO₂ (µg m⁻³) | 29.5 | 22.1 |
| O₃ (µg m⁻³) | 41.3 | 16.7 |
| EC (µg m⁻³) | 3.1 | 0.9 |
| SO₄ (ppb) | 3.2 | 1.0 |
| NO (ppb) | 28.6 | 4.0 |
| NO₂ (ppb) | 48.4 | 22.9 |
| O₃ (ppb) | 4.5 | 19.7 |
| CO (ppm) | 1.7 | 1.1 |
| VOC (ppb) | 154.0 | 96.0 |
| SOR | 0.66 | 0.85 |
| NOR | 0.17 | 0.26 |
| T (°C) | 1.2 | 3.0 |
| RH (%) | 53.7 | 67.6 |
| WS (m s⁻¹) | 1.0 | 1.0 |

Note: The data during the EP3 only includes the period when the PM2.5 component data is complete.

CRediT authorship contribution statement

Tao Ma: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. Fengkui Duan: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing. Yongliang Ma: Methodology, Resources, Validation. Qinqin Zhang: Data curation, Resources, Validation. Yunzhi Xu: Data curation, Resources, Validation. Wenguang Li: Data curation, Resources, Validation. Lidan Zhu: Data curation, Resources, Validation. Kebin He: Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

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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Appendix A. Supplementary data

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