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Drivers for the poor air quality conditions in North China Plain during the COVID-19 outbreak

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HIGHLIGHTS

- Both satellite data and ground measurements confirm improved NO\textsubscript{2} air quality.
- PM\textsubscript{2.5} varies between $-12.9 \$15.1\%$ driven by climate conditions.
- High PM\textsubscript{2.5} is maintained by intensive primary emission and increased oxidants.

GRAPHICAL ABSTRACT

Air Quality Trends Amid COVID-19

PM\textsubscript{2.5} Climate Response

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ABSTRACT

China’s lockdown to control COVID-19 brought significant declines in air pollutant emissions, but haze was still a serious problem in North China Plain (NCP) during late-January to mid-February of 2020. We seek the potential causes for the poor air quality in NCP combining satellite data, ground measurements and model analyses. Efforts to constrain COVID-19 result in a drop-off of primary gaseous pollutants, e.g., $-42.4\%$ for surface nitrogen dioxide (NO\textsubscript{2}) and $-38.9\%$ for tropospheric NO\textsubscript{2} column, but fine particulate matter (PM\textsubscript{2.5}) still remains high and ozone (O\textsubscript{3}) even increases sharply ($+84.1\%$). Stagnant weather during COVID-19 outbreak, e.g., persistent low wind speed, frequent temperature inversion and wind convergence, is one of the major drivers for the poor air quality in NCP. The surface PM\textsubscript{2.5} levels vary between $-12.9 \$15.1\%$ in NCP driven by the varying climate conditions between the years 2000 and 2020. Besides, the persistent PM\textsubscript{2.5} pollution might be maintained by the still intensive industrial and residential emissions (primary PM\textsubscript{2.5}), and increased atmospheric oxidants ($+26.1\%$ for ozone and $+29.4\%$ for hydroxyl radical) in response to the NO\textsubscript{2} decline (secondary PM\textsubscript{2.5}). Further understanding the nonlinear response between atmospheric secondary aerosols and NO\textsubscript{x} emissions is meaningful to cope with the emerging air pollution problems in China.

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1. Introduction

In late December of 2019, a novel coronavirus pneumonia named “COVID-19” emerged in Wuhan, a capital of 11 million people in Hubei province, China. Within the next month, the novel coronavirus spread quickly throughout the country, helped by the Chinese New Year migration, with Wuhan being a transport hub and major rail interchange in China. As of 21 January, the official data reported 440 confirmed cases and 9 deaths of COVID-19 in mainland China (http://www.nhc.gov.cn/).

The Chinese government launched an aggressive campaign to contain the spread of COVID-19. On 22 January, Hubei Province initiated the national lockdown response Level II, and a quarantine was issued to stop the travel in and out of Wuhan. As of 25 January, all the provinces in China had consecutively announced the public health emergency response Level I. The most serious epidemic control measures were implemented to contain the spread of COVID-19, including travel restrictions, factory closures, extended holidays, contact precaution, and closing of schools, stadiums, theatres and shopping malls. This pandemic was effectively controlled in early March, with the number of confirmed cases appearing each day has since plummeted in China.

China’s efforts to control COVID-19 seem to have curbed energy consumption and air pollutant emissions. Ongoing efforts to contain COVID-19 suppressed China’s industrial output by 15–30% across key industrial sectors (NBS, 2020). The traffic flow in major cities of China dropped by 60–90% during COVID-19 epidemic (http://jiaotong.baidu.com/top/). It was estimated that the carbon emission in China declined by 9.8% during COVID-19 compared to the same period of 2019, of which carbon emission from transportation sector declined mostly by 43.4% (Yue et al., 2020). Using tropospheric nitrogen dioxide (NO2) column data, it was calculated that nitrogen oxides (NOx) emission decreased by 50% in East China during 21 January to 9 February compared to that during 1–22 January 2020, and did not yet recover to their usual levels until late February in most provinces (Zhang et al., 2020).

The national lockdown brings significant air quality improvement (Chen et al., 2020; Sicard et al., 2020; Sun et al., 2020; Yue et al., 2020). The surface NO2 concentrations and tropospheric NO2 columns declined by 20–30% in China’s main urban clusters during February to March of 2020 than the same period of 2019, and surface fine particulate matter (PM2.5) and carbon monoxide (CO) declined by 24.9% and 17%, respectively, in China (Yue et al., 2020). Sicard et al. (2020) also found a substantial reduction in surface NOx (56%) and PM2.5 (42% in Wuhan and 8% in Europe) due to the global COVID-19 lockdown, but ozone (O3) increased in all cities (36% in Wuhan and 17% in Europe). Despite that, haze was still a serious air pollution problem during COVID-19 outbreak in North China Plain (NCP). The entire NCP region was shrouded in thick smog in late-January to mid-February of 2020, with the hourly concentration of surface PM2.5 remaining beyond 200 μg m⁻³ in the major cities of NCP (http://www.cnemc.cn/en/). The stifling haze was unexpected and aroused a hot debate in the public—why China’s coronavirus control efforts did not eliminate the poor air quality in NCP?

The persistent particulate pollution in China is typically associated with emissions (Geng et al., 2017; Wang et al., 2013), enhanced secondary production (Pu et al., 2020; Huang et al., 2020) and unfavorable meteorology (Ji et al., 2014; Jiang et al., 2015; Li et al., 2019; Yang et al., 2015; Zhang et al., 2015). Regional emission controls are effective in reducing the emissions and hence improving the air quality in several specific events, e.g., Beijing Olympic Games (Wang et al., 2010) and Asia-Pacific Economic Cooperation Conference (Wang et al., 2016). But some studies pointed out that the oxidation production of secondary aerosols was sensitive to the atmospheric oxidants concentrations, implying complex impacts of NOx and volatile organic compounds (VOCs) emission controls on secondary aerosol formation (Leibensperger et al., 2011; Pun and Seigneur, 2001; Tsipidou et al., 2008). They determined that the NOx emission reduction might cause an increase of aerosol in the VOCs-limited zone due to the enhanced atmospheric oxidation capacity. Recent evidence from field observations (Fu et al., 2020) also supported that the persistent heavy aerosol pollution in China over recent years was driven by the increased photochemical oxidants. Besides, the other causes for rapid haze increase include the stable boundary layer, weak ventilation and high humidity in winter that favored the accumulation and secondary formation of aerosol species (Wang et al., 2015; Yang et al., 2015; Zhang et al., 2015).

Because of the complex effects of emissions and meteorology, large unknowns still remain for the drivers of poor air quality in NCP during the COVID-19 outbreak. To address this issue, we try to seek the potential causes for the poor air quality in NCP and its link with the coronavirus control actions using satellite data, ground measurements and model analyses. Methods and data are presented in Sec. 2. Sec. 3 discusses the air quality trends in NCP and their potential drivers. Finally, a summary is presented in Sec. 4.
The aqueous SO$_2$ oxidation catalyzed by mineral ions and heterogeneous uptakes of SO$_2$, NO$_2$, nitrogen trioxide (NO$_3$), nitrogen pentoxide (N$_2$O$_5$) and nitric acid (HNO$_3$) on mineral aerosols were added in MOSAIC to better represent the secondary aerosol formation (Li et al., 2019). The physical options contain RRTMG radiation scheme (Iacono et al., 2008), Noah land surface scheme (Ek et al., 2003), Lin microphysics scheme (Lin et al., 1983) and YSU boundary layer scheme (Noh et al., 2003).

### 2.3. Numerical experimental designs and emission reduction scenarios

Ten WRF-Chem simulations are designed in Table 1. In the BASE simulation, the anthropogenic emissions in China remain unchanged as the usual levels ($E_{\text{BASE}}$), without regard to the COVID-19 controls. The CTL20 simulation is the same as BASE, but designed with modulated emissions ($E_{\text{CTL}}$) considering the impacts of epidemic control measures on power, industry, transportation and residential sectors. The differences between CTL20 and BASE simulations are calculated to show the impacts of emission controls during the COVID-19 outbreak on particulate pollution. Four additional control simulations (CTL00–CTL15) are conducted with the same emissions ($E_{\text{CTL}}$) as CTL20, but driven by varied climatic data every five years in 2000–2015. The CTL00–CTL20 simulations are designed to calculate the impacts of climate conditions on particulate pollution in NCP. Besides, another four sensitivity simulations (CTL20-EM25, CTL20-EM50, CTL20-NO25 and CTL20-NO50) are designed to illustrate the responses of primary and secondary VOCs and PPM$_{2.5}$ components to different emission reduction scenarios. In the CTL20-EM25 and CTL20-EM50 simulations, the emission reductions for all trace gases and particulate matter due to the COVID-19 lockdown are increased by 25% and 50%, respectively. In the CTL20-NO25 and CTL20-NO50 simulations, the emissions reductions of NO$_x$ due to the COVID-19 lockdown are further increased by 25% and 50%, respectively.

Anthropogenic emissions in China are adopted from Multi-resolution Emission Inventory for China (MEIC) that is developed by Tsinghua University (available at http://meicmodel.org), and updated to the usual levels of 2020 based on the annual statistical data of provincial emissions since 2016 (Chen et al., 2019; MEP, 2017; NBS, 2020). The timeline for the COVID-19 epidemic control in China is defined in Fig. 1.

### Table 1

| Experiment | Meteorological input | Anthropogenic emissions |
|------------|----------------------|-------------------------|
| BASE       | FNL in 2020          | Usual levels in 2020 ($E_{\text{BASE}}$) without regard to COVID-19 controls |
| CTL00      | FNL in 2020          | In CTL00–CTL20, emissions from power plant, industry, transportation and residential sectors are modulated considering the epidemic control measures ($E_{\text{CTL}}$) based on activity data |
| CTL15      | FNL in 2015          | Same as CTL20, but emissions reductions due to COVID-19 lockdown are further increased by 25%, i.e., $E_{\text{CTL}} - 25\% \times (E_{\text{BASE}} - E_{\text{CTL}})$ |
| CTL10      | FNL in 2010          | Same as CTL20, but emissions reductions due to COVID-19 lockdown are further increased by 50%, i.e., $E_{\text{CTL}} - 50\% \times (E_{\text{BASE}} - E_{\text{CTL}})$ |
| CTL05      | FNL in 2005          | Same as CTL20, but the emission reductions due to COVID-19 lockdown are further increased by 25% |
| CTL00      | FNL in 2000          | Same as CTL20, but the emission reduction of NO$_x$ due to COVID-19 lockdown is further increased by 50% |
| CTL20-EM25 | FNL in 2020          | Same as CTL20, but the emission reduction of NO$_x$ due to COVID-19 lockdown is further increased by 25% |
| CTL20-EM50 | FNL in 2020          | Same as CTL20, but the emission reduction of NO$_x$ due to COVID-19 lockdown is further increased by 50% |
| CTL20-NO25 | FNL in 2020          | Same as CTL20, but the emission reduction of NO$_x$ due to COVID-19 lockdown is further increased by 50% |
| CTL20-NO50 | FNL in 2020          | Same as CTL20, but the emission reduction of NO$_x$ due to COVID-19 lockdown is further increased by 50% |

Fig. 1. Two-nested WRF-Chem modelling domain (a) and monitoring stations (b). The epidemic control time is marked with shaded color in panel (b). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
The epidemic control and consequent emission decline initially occurred near Wuhan and quickly spread to the whole country as more regions adopted quarantine measures (Fig. 1). The air pollutant emissions slowly rebounded to pre-pandemic levels in March of 2020 (Zhang et al., 2020).

To estimate the emission reductions due to COVID-19, we scale China’s emissions data from power, industry, transportation and residential sectors based on the social economic activity data between 2019 and 2020, in a similar way as some recent researches (Huang et al., 2020; Wang and Su, 2020; Yue et al., 2020). Traffic emissions are reduced using a province-level emission reduction ratio, according to the dynamic traffic flow monitored at major cities of China (Table 2; http://jiaotong.baidu.com/top/). The traffic flow dropped by 52–99% during the COVID-19 epidemic, and Hubei and Henan saw the most rigorous traffic restrictions. For power sector, the electricity demand remained far below its usual level, and the national thermal power generation in January–February of 2020 dropped by 8.9% than that in 2019 (NBS, 2020). Emission from power plants is then assumed to decline by 8.9%. For key industrial sectors, the outputs of cement, chemicals and rubber fell by 15–30%, while the output of steel remained nearly unchanged (NBS, 2020). The emission from industrial sector is thus assumed to decline by ≈15% during COVID-19 lockdown. For residential sector, emissions from commercial boilers and stoves were eliminated since the closing of entertainment venues, while emissions from residential heating increased by 10% because millions of people were on lockdown, according to the recent investigation by Liqiang (2020).

3. Results and discussions

3.1. Air quality trends in NCP during COVID-19 outbreak from ground and satellite observations

We first look into the perturbations to atmospheric composition in response to COVID-19 (Figs. 2–4). The COVID-19 lockdown across the NCP region initiated on 24 January of 2020 (Fig. 1b), thereafter defined as a critical date for COVID-19 outbreak. The surface concentrations for main gaseous and particulate air pollutants had since then declined substantially in China, with a nationwide average of 18.5 μg m⁻³ for NO₂, 2.7 μg m⁻³ for SO₂, 0.3 mg m⁻³ for CO and 17.4 μg m⁻³ for PM₂.5 between 1 January and 23 January and 24 January–22 February of 2020 (Fig. 2). The decrease of surface NO₂ mixing ratios ranges from 50.8 to 16.4 μg m⁻³, particularly in southern NCP and mid-eastern China. Conversely the surface O₃ level increases nearly in all cities, with a nationwide average of 17.3 μg m⁻³, in a similar pattern as NO₂ due to the nonlinear relationship to its precursor. Declining trends of surface PM₂.5 and CO concentrations are also visible at more than 75% sites beyond the cities adjacent to Beijing, with even faster reductions around Hebei, Henan and Shandong. The changes for surface SO₂ show large inhomogeneity and even opposite trends for adjacent areas, which could be possibly because of the still high industrial and power plant emissions. The results confirm the recently reported COVID-19 impacts on air quality across China (Sicard et al., 2020; Yue et al., 2020).

Table 2: Monitored traffic flux changes after China’s Spring Festival of 2020 in major regions (data available from http://jiaotong.baidu.com).

| Region     | Change | Region     | Change |
|------------|--------|------------|--------|
| Hebei      | −70.2% | Zhejiang   | −58.5% |
| Beijing    | −69.3% | Hubei      | −98.5% |
| Henan      | −93.4% | Hunan      | −83.4% |
| Shanxi     | −52.8% | Jiangxi    | −75.0% |
| Shaanxi    | −64.9% | Guangdong  | −74.4% |
| Shandong   | −71.7% | Guangxi    | −68.3% |
| Jiangsu    | −62.1% | Ningxia    | −68.1% |
| Anhui      | −78.9% | Gansu      | −62.2% |
| Heilongjiang| −22.5% | Jilin      | −51.5% |
| Liaoning   | −27.7% | Inner Mongolia | −30.5% |

Several cities that are most severely affected by this persistent haze in NCP are selected as targets, namely Beijing, Tianjin, Shijiazhuang, Baoding and Tangshan. Two-month monitoring data in NCP suggest that the efforts to control coronavirus did result in a drop of primary gaseous pollutants between 1 and 23 January and 24 January–22 February, e.g., −24.0 μg m⁻³ (−42.4%) for NO₂, −1.4 μg m⁻³ (−9.6%) for SO₂ and −0.3 mg m⁻³ (−16.5%) for CO averaged over the five typical cities (Fig. 3). Despite that, the surface PM₂.5 concentration still remains high (−6.7%), and surface O₃ even increases sharply (+84.1%) in NCP after the COVID-19 outbreak. The entire NCP region was shrouded in thick smog (154.7 μg m⁻³ for average PM₂.5 concentration) in late-January to mid-February of 2020, with two peaks around the Spring Festival (24–28 January) and Lantern Festival (8–13 February; Fig. 3). The high proportion of nitrate in PM₂.5, i.e., 22.2% for 24–28 January and 26.8% for 8–13 February, is in accordance with recent observations in northern China (Shao et al., 2018; Zhang et al., 2018) and synchronous measurements in Shanghai (19.5%; Fig. 3).

Comparisons of satellite images from OMI in 2020 and the same period in 2017–2019 also show a dramatic effect of the “economic slowdown” during COVID-19 outbreak on tropospheric NO₂ in China, a gas primarily coming from traffic, industry and power plant (Fig. 4). OMI satellite data give a clear drop-off of tropospheric NO₂ column in NCP (−51.8%) from January to February in 2020 along with the full-scale promotion of epidemic control over all China. Typically, there is always lower NO₂ around this time of year, e.g., −39.2% for NCP from January to February in 2017–2019, as many household heating and industrial activities in China declines (Li et al., 2017). But it is noted that the NO₂ level in NCP declines by 38.9% in February 2020 compared to the same period in 2017–2019, attributed to the quarantine measures to stop the spread of coronavirus.

3.2. Drivers for the poor PM₂.5 air quality conditions in NCP

3.2.1. Model validation

The model results in CTL20 generally reproduced the spatial-temporal patterns of meteorology and air quality in NCP. Fig. S1 compares the modeled surface meteorology with real observations in five typical cities of NCP. The temporal patterns and magnitudes of temperature and relative humidity are reasonably well simulated, with a correlation coefficient of 0.79 and 0.64, and a mean bias (MB) of 0.52°C and −16.5%, respectively. Underestimation of specific humidity is a common phenomenon in the WRF simulation, which might be attributed to the influence of land surface conditions (Li et al., 2017; Yan et al., 2020) and boundary layer parameterizations (Bhati and Mohan, 2018; Gomez-Navarro et al., 2015) on weather forecast. Slight overestimation of wind speed (0.18 m s⁻¹) in the simulation might be because of the unresolved topography in WRF (Jimenez et al., 2013; Li et al., 2014).

The predicted surface PM₂.5 mass concentrations in NCP also compare well with measurements (Fig. S2), with a correlation coefficient of 0.65, a total MB of −9.22 μg m⁻³ and a normalized mean bias (NMB) of −0.12. The model is particularly successful in predicting the locations of maximum PM₂.5 concentrations along the Beijing, Tianjin, southern Hebei and Henan city belt (Fig. 5). This region saw a sharp increase of daily-average PM₂.5 from tens of μg m⁻³ to more than 150 μg m⁻³ during COVID-19 outbreak, exceeding the 2nd limit of National Ambient Air Quality Standard (75 μg m⁻³) by more than twofold. But it tends to seriously underestimate the PM₂.5 observations in the vicinity of southern NCP on Lunar New Year’s Eve (24 January), like Shanxi and Henan, which might be due to the missing of firework emissions in the emission inventory. Further evaluations of major gaseous pollutants (SO₂, NO₂, O₃ and CO) (Fig. S2) also indicate that the model is able to simulate the atmospheric pollution in NCP, with a MB of −16.3, 16.1 and 20.5 μg m⁻³ for O₃, NO₂ and SO₂, and −0.4 mg m⁻³ for CO, respectively. Comparisons between the CTL20 and BASE simulations confirm that the assumed emission reduction scenario results in better model performance for main gaseous pollutants in NCP. The model
3.2.2. Unfavorable weather conditions during COVID-19 outbreak

Local meteorology has deterministic impacts on pollution processes. Combining meteorological data and model results, we find that the weather conditions during COVID-19 outbreak are unconducive to the dispersion of air pollutants in NCP, e.g., persistently low wind speed biases for NO$_2$, SO$_2$ and O$_3$ are reduced by 29.9%, 15.3% and 23.0% in CTL20 during the post-COVID-19 period compared to that in BASE (data not shown here).

Fig. 2. Spatial distributions for the changes of observed aerosol and gaseous pollutants concentrations in China before and after COVID-19 outbreak.
(less than 1 m s\(^{-1}\)) lasting from late-January to early-February (Fig. S1), and sometimes strong surface temperature inversion (Fig. 6). From the temperature and wind speed profiles in Beijing (Fig. 6), the near-surface temperature inversion intensity reached up to 5-15 °C on these seriously polluted days (e.g., 26 January and 12 February), leading to a reduction of boundary layer height by 1/2-2/3 than the normal height on clean days. Meanwhile, the wind speeds on hazy days remained below 7 m s\(^{-1}\) throughout the atmospheric boundary layer, nearly half that on clean days (Fig. 6b). The stagnant weather conditions allow the local accumulation of high PM\(_{2.5}\) concentrations in NCP.

Analysis of the simulated surface PM\(_{2.5}\) concentrations and wind fields (Fig. 7) also shows favorable circulation characteristics for...
Fig. 4. Tropospheric NO$_2$ column ($10^{15}$ molecules cm$^{-2}$) from OMI in January–February of 2020 (a, b) and the same period in 2017–2019 (c, d).

Fig. 5. Pattern comparisons of the simulated daily-average surface PM$_{2.5}$ concentrations (shaded areas) and observed data (dots).
persistent particulate pollution in NCP. In the "24–28 January" episode, the stagnant air and surface wind convergence in NCP allowed the rapid accumulation of air pollutants and secondary aerosol production. A severe regional haze layer formed stretching from the NCP region towards mid-eastern China through transport by the dominant north wind. In the "8–13 February" episode, affected by the southerly wind and topography effect of Yan Mountain, surface cyclonic circulations formed and trapped the polluted air masses near Beijing, Tianjin and southern Hebei, leading to a rapid increase of PM$_{2.5}$ in NCP. After then, the prolonged haze pollution was cleared by the sudden wind shift to dry, cold north wind and the fast increase of wind speed to nearly 10 m s$^{-1}$ (Fig. S1).

Model results from CTL00–CTL20 further illustrate the role of climate conditions in this persistent particulate pollution covering NCP. Figs. 8 and 9 compare the simulated surface PM$_{2.5}$ concentrations, pressure fields and essential weather elements, i.e., temperature, humidity, planetary boundary layer height (PBLH) and wind in the CTL00–CTL20 experiments. Generally, climate anomaly determines the

Fig. 6. Observed vertical profiles of temperature and wind speed in Beijing on clean days (dashed lines) and polluted days (solid lines) during COVID-19 outbreak.

Fig. 7. Simulated surface average PM$_{2.5}$ concentrations (shaded contour) and wind fields (vectors) for the two typical hazy processes during COVID-19 outbreak: (a) 24–28 January and (b) 8–13 February.
spatial patterns and concentration levels of surface PM$_{2.5}$ in China (Fig. 8). The PM$_{2.5}$ levels varied between $-12.9$ to $+15.1\%$ in NCP driven by the varying climate conditions between 2000 and 2020. The simulated surface average PM$_{2.5}$ concentrations in NCP were 67.9, 57.4, 51.4, 58.1 and 59.9 $\mu$g m$^{-3}$, respectively, in CTL00–CTL20. The particulate pollution in NCP was most serious for the years 2000 (67.9 $\mu$g m$^{-3}$) and 2020 (59.9 $\mu$g m$^{-3}$), with broader influencing sphere covering northern to mid-eastern China and higher PM$_{2.5}$ concentrations exceeding 80 $\mu$g m$^{-3}$.

Analysis of the weather fields in CTL00–CTL20 (Fig. 9a) points out that the concentration level of PM$_{2.5}$ is negatively correlated to wind speed ($R = -0.933$) and boundary layer height ($R = -0.927$), and vice versa positively correlated to atmospheric humidity ($R = 0.656$). The calculated frequency distribution of wind in NCP for the CTL00–CTL20 climate scenarios shows that the dispersion conditions in CTL20 are favorable for the haze formation. The average wind speed in CTL20 remains low (3.9 m s$^{-1}$), and the frequency of light and calm wind (below 2 m s$^{-1}$) reaches up to 40.3%, compared to the mean levels of 27.7–41.2% in other climate scenarios (Fig. 9b). The NCP region is normally controlled by surface high pressure center in winter and the winds originate from the polluted industrial regions of Beijing-Tianjin-Hebei (Fig. 9c). Besides, in the climatologically dry winter season, the atmospheric humidity in CTL20 is larger than the usual levels, with a mean relative humidity of 52.2% near the surface and a maximum increase by 23.1%, facilitating multiphase reactions for aerosol formation and growth (Fig. 9a). Consistent with the increase in atmospheric humidity and the decrease in wind speed in CTL20, the atmospheric boundary layer height in NCP declined (403.7 m) during the COVID-19 lockdown, inducing a stable boundary layer and consequently producing high PM$_{2.5}$ levels. The climate conditions in CTL20 are featured by unusually stable atmosphere (404 m), stagnant air (3.9 m s$^{-1}$) and high humidity (52.2%; Fig. 9a), favoring the rapid accumulation and oxidation production of atmospheric aerosols.

3.2.3. Response of air quality to the coronavirus emission controls
The COVID-19 outbreak forces large changes in China’s socioeconomic activities, of which transportation sector seems to be most affected. The estimated emission reductions for main trace gases and primary PM$_{2.5}$ calculated from activity data are presented in Fig. S3. We observe a very strong decrease of NO$_x$, SO$_2$, CO and PM$_{2.5}$ emissions.
across northern and mid-eastern China attributed to the COVID-19 measures. The inferred emission reduction ratios range from −13.1% to −49.8% for NOX, −0.4% to −15.6% for SO2, −0.6% to −31.6% for CO, and −0.9% to −15.7% for primary PM2.5 at the provincial level (Table 3). NOx emitted from the combustion of coal fuels and the exhaust of urban vehicles is the major air pollutant affected by coronavirus controls, particularly in Hubei (−46.1%) and Henan (−49.8%). Provinces where the COVID-19 outbreak is first recorded or very strict lockdown regulations are adopted. In the NCP region, it is estimated that the unprecedented quarantine from 24 January to 17 February resulted in a dramatic reduction of air pollutants emissions, i.e., −6.9 × 10^8 ton (−33.1%) for NOX, −9.8 × 10^8 ton (−9.3%) for SO2, −2.6 × 10^8 ton (−12.7%) for CO and −1.3 × 10^8 ton (−7.4%) for PM2.5. The estimated NOx emission reduction in China using activity data (−13.1% to −49.8%) is comparable to the change in tropospheric NO2 column from OMI during the lockdown period (−38.9% in NCP; Fig. 4) and some recent reports using a top-down emission inverse algorithm (−20% to −50% from early January to mid-February in most provinces) (Ding et al., 2020; Miyazaki et al., 2020).

Model results also find that the emission controls during COVID-19 clearly improve the air quality of major primary air pollutants in NCP (Fig. 10), such as the surface NO2, SO2 and CO concentrations by −31.3, −8.3 and −8.2%, respectively. Nevertheless, the surface O3 mixing ratio in NCP increases sharply by 26.1% after the COVID-19 controls, resulting from the nonlinear relationship to its precursor NOx (Seinfeld and Pandis, 2006). The response of particulate air quality to the coronavirus emission controls seems more complicated (Fig. 10), with surface PM2.5 decreasing by 7.1% in NCP. The lockdown saw obviously lower emissions on road, but nearly unchanged emissions from emission-intensive industries (NBS, 2020) and household heating. The primary PM2.5 components, which mainly come from industrial and residential sectors (e.g., 49.7% and 38.8% in MEL3), thus still remain high (−41.1%) during the COVID-19 outbreak (Fig. 11). The oxidation production of secondary aerosol components depends not only on the abundance of their precursors (e.g., NOx and SO2), but also the atmospheric oxidizing capacity (e.g., O3 and hydroxyl radical (OH)). The emission controls of gaseous precursors NOx (−33.1%) and SO2 (−9.3%) seem to be less effective in reducing winter fine particles, which only lowers surface nitrate concentration by 11.7%, and even increases sulfate concentration (+2.4%) in NCP during COVID-19 outbreak.

The calculated nitrogen oxidation ratio (NOR) and sulfur oxidation ratio (SOR) on lockdown days are 10.6% and 16.9% higher in CTL20 than that in BASE. The increased NOR and SOR indicate that the decreased SNA formation in response to the COVID-19 emission controls is partly offset by the enhanced atmospheric oxidation capacity. To be specific, we focus on the response of nitrate to NOx emission during COVID-19 outbreak. The formation of nitrate involves multiphase chemical reactions, including the NO2+OH→HNO3 gas-phase oxidation and the heterogeneous hydrolysis of nitrogen pentoxide (N2O5) (He et al., 2018; Pathak et al., 2011). NO2 is key in atmospheric chemistry and serves as an important precursor for both ozone and secondary aerosol. The nonlinear response between nitrate and NOx emission in NCP might be associated with the increased atmospheric oxidants in CTL20, e.g., O3 (+26.1%) and OH (+29.4%), which subsequently facilitated the conversion of NOx to nitrate. It is noted that despite the nitric acid (HNO3) concentration in CTL20 drops by −25.6% in response to the COVID-19 NOx emission control, the concentrations of N2O5 (+14.4%) and nitrogen trioxide (NO3: +41.8%) increase markedly compared to that in BASE simulation (Fig. 11), which is produced from the NO2→NO3→N2O5 chemical reaction and is a crucial intermediate product for nitrate.

The sensitivity simulations of CTL20-NO25 and CTL20-NO50 also highlight that the emission reduction of NOx alone is less effective in altering the PM2.5 concentration and components (Fig. 11). The concentrations of nitrate, sulfate, ammonium and PM2.5 change by −6.2%, +15.4%, −3.8% and −1.8% after 25% cut of NOx emission in CTL20-NO25, and by −24.9%, +34.6%, −18.3% and −8.5% after 50% cut of NOx emission in CTL20-NO50 compared to CTL20. The insensitive response of secondary aerosols to NOx emission may be explained by the increased atmospheric oxidizing capacity (e.g., +22.0% for O3 and +36.4% for OH in CTL20-NO25) and the still high intermediate products for nitrate (e.g., +4.7% for N2O5 and −8.5% for HNO3 in CTL20-NO25) compared to CTL20. Comparison of the emission reduction scenarios in CTL20-EM25 and CTL20-EM50 further confirms the complex chemical responses of primary and secondary PM2.5 to emission control strategies (Fig. 11). More stringent emission reductions for trace gases and PM2.5 by 25% and 50% on the basis of ECTD result in concurrent declines of both primary and secondary PM2.5 components (−19.0% in CTL20-
Table 3
Estimated emission reductions of air pollutants (%) in major regions of China from 24 January to 17 February in 2020 due to the COVID-19 control.

| Region       | NO₂  | SO₂  | CO   | PM₁₀₅ | Region       | NO₂  | SO₂  | CO   | PM₁₀₅ |
|--------------|------|------|------|--------|------------|------|------|------|--------|
| Beijing      | -29.6| -11.8| -13.3| -5.0   | Lisoning    | -15.7| -10.9| -5.5 | -4.4   |
| Tianjin      | -281 | -13.1| -16.8| -6.2   | Fujian      | -36.5| -15.3| -21.7| -8.2   |
| Hebei        | -31.5| -9.0 | -10.5| -5.7   | Jiangxi     | -42.5| -11.0| -14.2| -8.0   |
| Shanxi       | -21.3| -4.9 | -6.5 | -6.6   | Guangdong   | -41.0| -15.6| -31.6| -12.2  |
| Inner Mongolia| -13.6| -6.5 | -1.8 | -3.0   | Guangxi     | -39.2| -14.4| -15.4| -8.1   |
| Shandong     | -33.3| -9.6 | -13.4| -8.9   | Hainan      | -29.7| -14.6| -15.8| -4.3   |
| Henan        | -49.8| -11.0| -15.6| -9.8   | Chongqing   | -36.8| -11.8| -8.7  | -3.6   |
| Shanghai     | -26.5| -12.9| -24.4| -15.7  | Sichuan     | -33.4| -11.8| -9.5  | -1.9   |
| Jiangsu      | -29.1| -14.9| -15.8| -7.7   | Guizhou     | -28.8| -0.4 | -0.6  | -0.9   |
| Zhejiang     | -31.8| -14.6| -29.8| -12.4  | Yunnan      | -40.9| -8.9 | -15.4| -6.3   |
| Anhui        | -40.4| -11.6| -5.9 | -3.0   | Shaanxi     | -28.1| -4.6 | -8.8  | -4.2   |
| Hubei        | -46.1| -5.7 | -9.2 | -4.7   | Gansu       | -30.0| -7.4 | -5.5  | -1.7   |
| Hunan        | -39.4| -5.2 | -6.8 | -3.0   | Qinghai     | -30.1| -8.7 | -9.9  | -5.2   |
| Heilongjiang | -13.1| -2.9 | -1.6 | -1.4   | Ningxia     | -25.6| -10.4| -16.8| -8.3   |
| Jilin        | -20.2| -8.2 | -3.8 | -1.7   | Xinjiang    | -22.7| -11.1| -17.0| -10.1  |

Fig. 10. Impacts of COVID-19 emission controls on surface air quality during 24 January to 17 February of 2020.

Fig. 11. Impacts of six emission scenarios on the concentrations of PM₂.₅ components, O₃, NO₂ and the main intermediate products of nitrate (N₂O₅ and HNO₃) during 24 January to 17 February of 2020. EM25 and −39.4% in CTL20-EM50 for PM₂.₅), yet with different responses for primary and secondary species. Secondary aerosols show much smaller changes (−14.1% in CTL20-EM25 and −28.9% in CTL20-EM50) with the emission reductions, compared with primary aerosols (−23.1% in CTL20-EM25 and −45.7% in CTL20-EM50). Recent evidence from intensive observation and numerical simulation also highlighted smaller response of secondary aerosols to the COVID-19 lockdown (Huang et al., 2020; Le et al., 2020; Sun et al., 2020).

4. Conclusion
China’s efforts to contain COVID-19 suppressed the socio-economic activities and emissions, but the NCP region was still shrouded in thick smog in late-January to mid-February of 2020. We discuss the potential links between the poor air quality conditions in NCP and coronavirus control actions combining satellite data, ground measurements and model analyses. The national lockdown brought dramatic declines in air pollutant emissions, e.g., −33.1%, −9.3%, −12.7% and −7.4% for NOₓ, SO₂, CO and PM₂.₅, respectively, from 24 January to 17 February in NCP. The COVID-19 effects on improved NO₂ air quality in NCP are confirmed by satellite data (−38.9% for tropospheric NO₂ column) and ground measurements (−42.4% for surface NO₂ concentration). Stagnant weather in NCP during the COVID-19 outbreak, e.g., persistent low wind speed,
frequent temperature inversion and wind convergence, are the major drivers for the poor air quality. The surface PM$_{2.5}$ levels in NCP vary between ~12.9~+15.1% driven by the varying climatic conditions from 2000 to 2020. Besides, the persistent PM$_{2.5}$ pollution might be maintained by the still intensive industrial and residential emissions (primary PM$_{2.5}$), and the enhanced atmospheric oxidation capacity (e.g., +26.1% for O$_3$ and +29.4% for OH) as a nonlinear response to NO$_x$ declines (secondary PM$_{2.5}$). This work highlights that more scientific and stringent emission controls and climate adaptation strategies are required to attain the synergetic control of air pollution and to cope with the emerging air pollution problems in China.

Some uncertainties still exit in our assessment. The emission reductions due to COVID-19 are estimated based on activity data from key sectors. This method might obscure the detailed spatiotemporal emission information due to the difficulty in gathering fine-resolution statistical data. Instead, a top-down approach using an inverse algorithm and multiple satellite observations has been demonstrated to provide accurate and quick emission estimates during COVID-19 lockdown (Ding et al., 2020; Miyazaki et al., 2020). They found that the Chinese NO$_x$ emission was reduced 20~50% for cities, 40% for power plants, and 15~40% for maritime transport.

Atmospheric ammonia (NH$_3$) that is emitted from fertilizer application, livestock, biomass burning, chemical industry, waste disposal and transportation acts as a critical neutralizing species for SNA production and efficient haze mitigation (Liu et al., 2019). China is known as the world’s top emitter of NH$_3$, but the emission estimate for NH$_3$ has a large uncertainty of up to ±153% (Kurokawa et al., 2013; Liu et al., 2019). Compared to the process-based NH$_3$ estimates in China, e.g., PKU-NH$_3$ (Huang et al., 2012), the MEIC NH$_3$ inventory agrees well in temperate zones but is significantly higher in tropical zones, due to the discrepancies in derived emission factors (Li et al., 2017). Improved and updated emission estimates for NH$_3$ are needed to accurately simulate the secondary aerosol production and its emission responses.

Besides, secondary organic aerosol (SOA) formed from the oxidation of volatile organic compounds (Seinfeld and Pandis, 2006) is also an important component of PM$_{2.5}$ in China (Huang et al., 2014; Zhao et al., 2016). The concentration, composition and properties of SOA showed complicated responses to the emissions of NO$_x$ and VOCs (Feng et al., 2019; Tsipidou et al., 2008; Xu et al., 2019). However, the simulation of SOA is usually seriously underestimated by more than tenfold in China because of the poor understanding of its precursors, chemical mechanisms and physicochemical characterization (Jiang et al., 2012; Li et al., 2011; Robinson et al., 2007). Further understanding and improvement of SOA simulation are needed to enhance the understanding of aerosol and photochemistry feedback in China.

CRediT authorship contribution statement

Mengmeng Li: Methodology, Writing - original draft, Software. Shu Li: Software, Supervision. Bingliang Zhuang: Resources, Data curation. Qingyan Fu: Data curation. Ming Zhao: Validation. Hao Wu: Validation. Jane Liu: Writing - review & editing. Eri Saikawa: Formal analysis. Kuo Liao: Visualization.

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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2020.118103.

Data availability statement

The WRF-Chem model version 4.1 is available at http://www2.mmm.ucar.edu/wrf/users/downloads.html. The NCEP FNL data are accessible at the National Center for Atmospheric Research (NCAR) Research Data Archive (https://rda.ucar.edu/datasets/ds083.2/). The surface meteorological data are downloaded from Integrated Surface Database (https://www.ncdc.noaa.gov/isd/data-access), and the sounding meteorological data are downloaded from Integrated Global Radiosonde Archive (https://www.ngdc.noaa.gov/pub/data/igra/). The air pollutants and aerosol species data are provided by China National Environmental Monitoring Center and Shanghai Environmental Monitoring Center, which are archived at https://doi.org/10.6084/m9.figshare.12449663.v1. The OMI products are provided by the NASA Goddard Space Flight Center (https://acd-ext.gsfc.nasa.gov/Data_services). Model outputs from WRF-Chem could be accessible upon request via hard drives from the Dr. Mengmeng Li, Email address: mengmengli2015@nju.edu.cn.

References

Berge, E., Huang, H.C., Chang, J., Liu, T.H., 2001. A study of the importance of initial conditions for photochemical oxidant modeling. J. Geophys. Res. Atmos. 106, 13477–13493.

Bhats, S., Mohan, M., 2018. WRF-urban canopy model evaluation for the assessment of heat island and thermal comfort over an urban aired in India under varying land use/land cover conditions. Geoci Lett 5.

Carvalho, D., Rocha, A., Gomes-Genteira, M., Santos, C.S., 2014. WRF wind simulation and wind energy production estimates forced by different reanalysis: comparison with observed data for Portugal. Appl. Energy 117, 116–126.

Chen, H., Hau, J., Fu, Q., Duan, X., Xiao, H., Chen, J., 2020. Impact of quarantine measures on chemical composition of PM$_{2.5}$ during the COVID-19 epidemic in Shanghai, China. Sci. Total Environ. 743.

Chen, Z.Y., Chen, D.M., Wan, W., Zhang, Y., Kwan, M.P., Chen, B., Zhao, B., Yang, L., Gao, B.B., Li, R.Y., Xu, B., 2019. Evaluating the "2/6/26” regional strategy for air quality improvement during two air pollution alerts in Beijing: variations in PM$_{2.5}$ concentrations, source apportionment, and the relative contribution of local emission and regional transport. Atmos. Chem. Phys. 19, 6879–6891.

Ding, J., van der A, R., Eikes, H., Miljling, B., Stavrazou, T., van Geffen, J., Veekind, J., 2020. NOx emissions reduction and rebound in China due to the COVID-19 crisis. Geophys. Res. Lett. 47.

Durre, I., Vose, R.S., Wurzel, D.B., 2006. Overview of the integrated global radiosonde archive. J. Clim. 19, 53–68.

Ek, M.B., Mitchell, K.E., Lin, Y., Rogers, E., Grumm, P., Koren, V., Gayno, G., Tarpley, J.D., 2003. Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale eta model. J. Geophys. Res. Atmos. 108.

Fahey, K.M., Pandis, S.N., 2001. Optimizing model performance: variable size resolution in cloud chemistry modeling. Atmos. Environ. 35, 4471–4478.

Feng, T., Zhao, S.Y., Bei, N.F., Wu, J.R., Liu, S.X., Li, X., Liu, Q., Yan, Q.C., Wang, Y.C., Zhou, W.J., Can, J.J., Li, G.H., 2019. Secondary organic aerosol enhanced by increased atmospheric oxidizing capacity in Beijing-Tianjin-Hebei (BTH), China. Atmos. Chem. Phys. 19, 7429–7443.

Fu, X., Wang, T., Gao, J., Wang, P., Liu, Y.M., Wang, S.X., Zhao, B., Xue, L.K., 2020. Persistent heavy winter nitrate pollution driven by increased photochemical oxidants in northern China. Environ. Sci. Technol. 54, 3881–3889.

Gaudel, A., Cooper, O.R., Areallet, G., Barret, B., Boyard, A., Burrows, J.P., Clerbaux, C., Coheur, P.F., Cuesta, J., Cuevas, E., Doniki, S., Dufour, G., Ebojie, B., Forest, G., Garcia, O., Granados-Munoz, M.J., Hamigan, J.W., Haze, F., Hanster, B., Huang, G., Furmann, H., Jaffe, D., Jones, N., Kalabokas, P., Kerridge, B., Kulawik, S., Latter, B., Leblanc, T., Le Flochmoen, E., Lin, W., Liu, J., Liu, X., Mahieu, E., McClure-Begley, A., Neu, J.L., Osman, M., Palm, M., Petetin, H., Petropavlovskikh, I., Querel, R., Rahpoe, N., Rozanov, A., Schultz, M.G., Schwab, J., Siddans, R., Smale, D., Steinhaber, M., Tanimoto, H., Tarasick, D.W., Thouret, V., Thompson, A.M., Trickl, T., Weatherhead, E., Wespes, C., Worden, H.M., Vigouroux, C., Xu, X., Zeng, G., Ziemke, J., 2018. Tropospheric Ozone Assessment Report: present-day distribution and trends of tropospheric ozone relevant to climate and global atmospheric chemistry model evaluation. Elementa:Sci Anthrop 6.
Miyazaki, K., Bowmann, K., Sekiya, T., Jiang, Z., Chen, C., Eskes, H., Ru, M., Zhang, Y., Shindell, D., 2020. Air quality response in China linked to the 2019 novel coronavirus (COVID-19) lockdown. J. Geophys. Res. Atmos. 125, 47–57.
NBS, 2020. National Bureau of Statistics, Beijing, China.
Noh, Y., Cheon, W.G., Hong, S.Y., Raasch, S., 2003. Improvement of the K-profile model for the planetary boundary layer based on large eddy simulation data. Bound-Lay Meteorol. 107, 401–427.
Pathak, R.K., Wang, T.W., 2011. Nighttime enhancement of PM\textsubscript{2.5} nitrate in ammonia-poor atmospheric conditions in Beijing and Shanghai: plausible contributions of heterogeneous hydrolysis of NO\textsubscript{2} and HNO\textsubscript{3} partitioning. Atmos. Chem. Phys. 11, 11833–11843.
Pun, B.K., Seigneur, C., 2001. Sensitivity of particulate matter nitrate formation to precursor emissions in the California San Joaquin Valley. Environ. Sci. Technol. 35, 2579–2587.
Robinson, A.L., Donahue, N.M., Shrivastava, M.K., Weitkamp, E.A., Sage, A.M., Grieshop, A.P., Lane, T.E., Pierce, J.R., Parrish, D.S., 2007. Rethinking organic aerosols: semivolatile emissions and photochemical aging. Science 315, 1259–1262.
Seinfeld, J.H., Pandis, S.N., 2006. Atmospheric Chemistry and Physics: from Air Pollution to Climate Change, second ed. John Wiley and Sons, Hoboken, NJ.
Shao, P.Y., Tian, H.Z., Sun, Y.J., Liu, H.J., Wu, B.B., Liu, S.H., Liu, X.Y., Wu, Y.M., Liang, W.Z., Wang, Y., Gao, J.J., Xue, Y.F., Bai, X.K., Liu, W., Lin, S.M., Hu, G.Z., 2018. Characterizing remarkable changes of severe haze events and chemical compositions in multi-size airborne particles (PM\textsubscript{2.5}, PM\textsubscript{2.5}–PM\textsubscript{10}) from January 2013 to 2016-2017 winter in Beijing, China. Atmos. Environ. 189, 133–144.
Shiu, L., Wang, T., Xie, M., Li, M., Zhao, M., Zhang, X., 2020. PM\textsubscript{2.5} fine particle and ozone during the CAPUM-VRD over Yangtze River Delta of China: characteristics and source attribution. Atmos. Environ. 203, 87–101.
Sidicard, F., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoliotti, E., Rodriguez, J., Calatayud, V., 2020. Amplified ozone pollution in cities during the COVID-19 lockdown. Sci. Total Environ. 742.
Smith, A., Lott, N., Vose, R., 2011. The integrated surface Database recent developments and partnerships. Bull. Am. Meteorol. Soc. 92, 704–708.
Sun, Y., Lei, L., Zhou, W., Chen, C., He, Y., Sun, J., Liu, H., Xu, W., Wang, J., Ji, D., Fu, F., Wang, Z., Wang, Y., 2020. Annual and diurnal variations of NO\textsubscript{x} and PAN in the southern Yangtze Delta region of China during winter 2016. J. Geophys. Res. Atmos. 124, 1092–1109.
Tan, T.Y., Pan, Y.P., Chen, J.M., Zhang, F.S., 2019. Impact of emission controls on air quality in Beijing, China: insights from six-year aerosol particle composition measurements during the Chinese New Year holiday. Sci. Total Environ. 742.
Tsimpidi, A.P., Karydis, V.A., Pandis, S.N., 2008. Response of fine particulate matter to emission changes of oxides of nitrogen and anthropogenic volatile organic compounds in the eastern United States. J Air Waste Manage 58, 1463–1473.
Wang, M.Y., Cao, C.X., Li, G.S., Singh, R.P., 2015. Analysis of a severe prolonged regional haze episode in the Yangtze River Delta, China. Atmos. Environ. 102, 112–121.
Wang, P., Xu, M., 2020. A preliminary assessment of the impact of COVID-19 on environment? A case study of China. Sci. Total Environ. 728.
Wang, S.X., Zhan, M., Xing, J., Wu, Y., Zhou, Y., Lei, Y., He, K.B., Fu, L.X., Hao, J.M., 2020. Quantifying the air pollutants emission reduction during the 2008 olympic games in Beijing. Environ. Sci. Technol. 44, 2490–2496.
Wang, Y., Zhang, Q.Q., He, K., Zhang, Q., 2013. Sulfate-nitrate-ammonium aerosols over China: response to 2000-2015 emission changes of sulfur dioxide, nitrogen oxides, and ammonia. Atmos. Chem. Phys. 13, 2635–2652.
Wang, Y.Q., Zhang, Y., Schauer, J.J., de Foy, B., Guo, B., Zhang, Y.X., 2016. Relative impact of emission controls and meteorology on air pollution mitigation associated with the Asia-Pacific Economic Cooperation (APEC) conference in Beijing, China. Atmos. Environ. 127, 66–79.
Xue, X., Li, Y., Zhou, H., Liu, Z., Cai, Z., Zhang, J., Liao, J., Liu, Z., Hao, L., 2020. Changes of anthropogenic carbon emissions and air pollutants during the COVID-19 epidemic in China (in Chinese). Trans Atmos Sci 43, 1625–1637.
Zaveri, R.A., Easter, R.C., Fast, J.D., Peters, L.K., 2008. Model for simulating aerosol processes (MAMP): Model description and application to urban aerosol. J. Geophys. Res. 113, B03422.
Zaveri, R.A., Peters, L.K., 1999. A new lumped structure photochemical mechanism for large-scale applications. J. Geophys. Res. 104, 30387–30415.
Zhang, Q., Quan, J.W., Tie, X.X., Li, X., Liu, Q., Gao, Y., Zhao, D.L., 2015. Effects of meteorology and secondary aerosol formation on visibility during heavy haze events in Beijing, China. Sci. Total Environ. 502, 578–584.
Zhang, R., Zhang, Y., Lin, H., Feng, X., Fu, T., Wang, Y., 2020. NO\textsubscript{x} emission reduction and recovery during COVID-19 in East China. Atmosphere-Basel 11, 433.
Zhang, Q., Wang, Y.M., Zhao, Y.Q., Zhang, Q., Jin, F., Xing, L., Chen, X., Wang, Z., Che, H.C., 2018. Chemical components, variation, and source identification of PM\textsubscript{2.5} during the heavy air pollution episodes in beijing in december 2016. J Meteorol Res. 32, 1473–1483.