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Heavy haze pollution during the COVID-19 lockdown in the Beijing-Tianjin-Hebei region, China

Xin Zhang\(^1\), Zhongzhi Zhang\(^2\), Zhisheng Xiao\(^2\), Guigang Tang\(^3\), Hong Li\(^2\), Rui Gao\(^2\), Xu Dao\(^3\), Yeyao Wang\(^3\), Wenxing Wang\(^1,2\)

\(^1\) Environment Research Institute, Shandong University, Qingdao 266237, China
\(^2\) State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Sciences, Beijing 100012, China
\(^3\) China National Environmental Monitoring Centre, Beijing 100012, China

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**Abstract**

To investigate the characteristics of particulate matter with an aerodynamic diameter less than 2.5 μm (PM\(_{2.5}\)) and its chemical compositions in the Beijing-Tianjin-Hebei (BTH) region of China during the novel coronavirus disease (COVID-19) lockdown, the ground-based data of PM\(_{2.5}\), trace gases, water-soluble inorganic ions, and organic and elemental carbon were analyzed in three typical cities (Beijing, Tianjin, and Baoding) in the BTH region of China from 5-15 February 2020. The PM\(_{2.5}\) source apportionment was established by combining the weather research and forecasting model and comprehensive air quality model with extensions (WRF-CAMx). The results showed that the maximum daily PM\(_{2.5}\) concentration reached the heavy pollution level (>150 μg/m\(^3\)) in the above three cities. The sum concentration of SO\(_4^{2-}\), NO\(_3^-\), and NH\(_4^+\) played a dominant position in PM\(_{2.5}\) chemical compositions of Beijing, Tianjin, and Baoding; secondary transformation of gaseous pollutants contributed significantly to PM\(_{2.5}\) generation, and the secondary transformation was enhanced as the increased PM\(_{2.5}\) concentrations. The results of WRF-CAMx showed obviously inter-transport of PM\(_{2.5}\) in the BTH region; the contribution of transportation source decreased significantly than previous reports in Beijing, Tianjin, and Baoding during the COVID-19 lockdown; but the contribution of industrial and residential emission sources increased significantly with the increase of PM\(_{2.5}\) concentration, and industry emission sources contributed the most to PM\(_{2.5}\) concentrations. Therefore, control policies should be devoted to reducing industrial emissions and regional joint control strategies to mitigate haze pollution.

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**Introduction**

Fine particulate matter (particulate matter with an aerodynamic diameter less than 2.5 μm, PM\(_{2.5}\)) is an important air pollutant in human health, ecological effect, and climate change (Ding et al., 2016; Gao et al., 2017; Zhang et al., 2015).

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\(\ast\) This article is dedicated to Professor Dianxun Wang.
\(\ast\) Corresponding authors.
E-mails: gaurui@caaes.org.cn (R. Gao), daoxy@cnemc.cn (X. Dao).

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Since 2013, with the implementation of the toughest-ever clean air policy in China, significant declines in PM$_{2.5}$ concentrations nationwide, the air quality has improved significantly. From 2013 to 2017, the estimated national population-weighted annual mean PM$_{2.5}$ concentrations decreased from 61.8 to 42.0 $\mu g/m^3$; the highest decrease (38%) in PM$_{2.5}$ was observed in the Beijing-Tianjin-Hebei (BTH) region, and the dominant contributions from anthropogenic emission abatements (Chen et al., 2019; Wang et al., 2019a; Zhang et al., 2019b). The annual mean PM$_{2.5}$ concentration of the BTH region and its surrounding areas (201 cities) was 57 $\mu g/m^3$ in 2019 (http://www.mee.gov.cn/hjzl/sthjzlx/zghjzkb/), but this value still exceeds the World Health Organization (WHO) standard level for the good health of 25 $\mu g/m^3$ (WHO, 2006). Moreover, heavy haze pollution events still occur frequently under adverse meteorological conditions.

Since December 2019, a novel coronavirus disease (COVID-19) outbreak was first identified in Wuhan and quickly expanded across China. The Chinese government has gradually taken a series of control measures to contain the epidemic, such as closed communities and restrict transportation. The control measures have significantly reduced the activity level of residents; coal, oil refining, steel output far below the same period levels in the past few years, and over 70% reductions in vehicle transportation and domestic flights (Chang et al., 2020; He et al., 2020). Thus, the atmospheric pollutant emissions from various sources have been reduced. Nevertheless, large-scale and heavy haze pollution with a high PM$_{2.5}$ mass concentration was observed in the BTH region after the Lantern Festival (8 February 2020). During this period, the major cities in the BTH region suffered at least one day of heavy haze pollution (PM$_{2.5}$ > 150 $\mu g/m^3$, NAAQS IV for daily PM$_{2.5}$ and heavy pollution limit for haze); especially Beijing, which suffered the worst air quality day since the 2019-2020 heating season (November 2019 to March 2020), and the daily PM$_{2.5}$ concentrations reached 207 $\mu g/m^3$ (http://www.cnemc.cn/).

In this study, we present results from analyses of PM$_{2.5}$ pollution characteristics in Beijing, Tianjin, and Baoding, the typical cities of the BTH region, and characteristics of chemical components of aerosol at urban sites in the above three cities. The weather research and forecasting model (version 3.5.1) and comprehensive air quality model with extensions (version 6.3) (WRF-CAMx) were used to perform numerical simulation analysis for PM$_{2.5}$ episodes; the inter-cities and regions transport to PM$_{2.5}$ concentration was calculated, and the contributions of different pollution sources to PM$_{2.5}$ were discussed. The present study aims to gain detailed clues of the haze event in the BTH region.

1. Materials and methods
1.1. Sites description and analysis datasets

The location of Beijing, Tianjin, and Baoding is an equilateral triangle, and the distance between cities is approximately 150 km (Fig. 1). The real-time data of PM$_{2.5}$, particulate matter with an aerodynamic diameter less than 10 $\mu m$ (PM$_{10}$), nitrogen dioxide (NO$_2$), sulfur dioxide (SO$_2$), carbon monoxide (CO), and ozone (O$_3$) were released to the public by China National Environmental Monitoring Centre (CNEMC) and obtained from the Air Quality Monitoring and Analysis Platform (https://quotsoft.net/air/). Mass concentrations of chemical compositions in PM$_{2.5}$ were obtained from BTH regional particulate matter chemical compositions monitoring network, including water-soluble inorganic ions (SO$_4^{2-}$, NO$_3^-$, NH$_4^+$, Cl$^-$, Ca$^{2+}$, K$^+$, Na$^+$, Mg$^{2+}$, F$^-$), organic carbon (OC) and elemental carbon (EC). The chemical compositions in PM$_{2.5}$ were observed at urban sites: CNEMC in Beijing (116.42°E, 40.04°N), Zhengshan north road in Tianjin (117.21°E, 39.17°N) and Yangguang north street in Baoding (115.48°E, 38.93°N). Meteorological data were obtained from the China Meteorological Data Service Centre (http://data.cma.cn/), including temperature, relative humidity, wind, and pressure. The height of planetary boundary layer (PBL) was simulated by WRF-CAMx. The online ambient observation was conducted from 5-15 February 2020, and the time resolutions of all the above data were 1 hour.

1.2. Model configuration

The WRF-CAMx model has been widely used for pollution simulation research, especially with Particulate Source Apportionment Technology (PSAT) (Li et al., 2013; Sun et al., 2018; Wagstrom et al., 2008). This study employed the WRF-CAMx model to simulate meteorological conditions, PM$_{2.5}$ variations, and source apportionment. The CAMx model was applied and configured using two-level nested modeling domains. A coarse-grid domain with a resolution of 36 km × 36 km was employed to cover the whole East Asia region. At a more local level, a fine-grid domain with a resolution of 12 km × 12 km was used, which covered most parts of northeastern China, including the BTH region and some surrounding provinces. The coarse-grid simulations were used to provide boundary conditions for the fine-grid simulations. All of the following analyses are based on the results from the fine-grid simulations (Zhang et al., 2017).

In order to distinguish the sources of pollutant transportation in the target cities, we reclassified the fine-grid domain into ten areas, including three target cities (1. Beijing; 2. Tianjin; 3. Baoding), four areas in other cities of Hebei Province (4. Zhangjiakou, Chengde, Qinhuangdao (ZCQ); 5. Tangshan (TS);
6. Langfang, Cangzhou (LC); 7. Shijiazhuang, Hengshui, Xingtai, Handan (SHXH), three areas in other provinces (8. Shandong Province (SD); 9. Shanxi Province (SX); 10. Other regions). For clarity, we displayed a diagram of regional redistricting in Appendix A Fig. S1.

Tropospheric Analysis datasets were provided by the Final Operational Global Analysis of the USA National Center for Environmental Prediction (NCEP FNL data). Emissions data of nature were calculated by the Model of Emissions of Gases and Aerosols from Nature Version 3 (MEGAN3) for estimating biogenic emissions (Guenther et al., 2020). Emissions data of anthropogenic activity were based on the Multi-resolution Emission Inventory for China (MEIC emission inventory Version 1.3 (http://www.meicmodel.org/)), which include PM$_{2.5}$, PM$_{10}$, CO, SO$_2$, nitrogen oxides (NO$_x$), black carbon (BC), OC, total suspended particulate (TSP), ammonia (NH$_3$), volatile organic compounds (VOCs), and carbon dioxide (CO$_2$). Furthermore, these pollutants were divided into six sources: industry, residential, transportation, power, agriculture, and other sources. The emissions in the 2-26 cities were updated to include the latest survey results. In particular, we have revised the emission data again during the COVID-19 lockdown to ensure the agreement between the simulated and observed values of pollutants (Appendix A Fig. S2) (Huang et al., 2020; Le et al., 2020; Lv et al., 2020; Meng et al., 2021).

2. Results and discussion

2.1. Overview of PM$_{2.5}$ concentrations

The temporal and spatial distributions of daily PM$_{2.5}$ concentrations at various sites in the BTH region during haze episodes are shown in Fig. 2. The daily PM$_{2.5}$ concentrations at all sites in the BTH region reached Class II of the National Ambient Air Quality Standard (NAAQS II, 75 $\mu$g/m$^3$) on 5-6 February 2020; air quality levels were good or moderate at different sites (MEE, 2012). After that, slight PM$_{2.5}$ pollution began to appear in the southeastern part of the BTH region on 7 February, and large-scaled heavy PM$_{2.5}$ pollution gradually appeared in the following days. From 9 to 11 February, the maximum daily PM$_{2.5}$ concentration exceeded 150 $\mu$g/m$^3$ at all sites of Beijing, Tianjin, and Baoding. Until 14 February, the daily PM$_{2.5}$ concentration in the BTH region dropped rapidly; then, the regional daily PM$_{2.5}$ concentrations were less than 35 $\mu$g/m$^3$ (NAAQS I) on 15 February, and the haze episode ended.

During heavy haze pollution episodes, the mean daily PM$_{2.5}$ concentrations of Baoding exceeded 150 $\mu$g/m$^3$ for five consecutive days and three, two days of Beijing and Tianjin (Table S1). The maximum daily PM$_{2.5}$ concentration of Beijing reached 207 $\mu$g/m$^3$ (12 February), and this was the most polluted day during the 2019-2020 heating season. The highest hourly PM$_{2.5}$ level at all sites of three cities was 330 $\mu$g/m$^3$, which appeared in the center of the cities’ triangle (Yufa site, Fig. 2), and this value was four times higher than the NAAQS II.

The ratios of PM$_{2.5}$/PM$_{10}$ were 1.20±0.36, 1.12±0.37, 0.81±0.11, and the correlation coefficients ($R^2$) were 0.96, 0.95, 0.99 in Beijing, Tianjin, and Baoding during the observed period, respectively. There was a reversal phenomenon between PM$_{2.5}$ and PM$_{10}$ under high humidity conditions in Beijing and Tianjin. This could be caused by the different monitoring methods of PM$_{2.5}$ and PM$_{10}$, and another critical factor is that the influence of water was not absolutely eliminated under high humidity (jiang et al., 2016; Pan et al., 2014).

2.2. Characteristics of PM$_{2.5}$ chemical compositions

Fig. 3 shows the time series of meteorological variables, pollutants concentrations, and PM$_{2.5}$ chemical compositions in Beijing, Tianjin, and Baoding from 5 to 15 February 2020. For PM$_{2.5}$ concentration, the site data closest to the chemical composition monitoring was used: Aoti site in Beijing, Huaihedao site in Tianjin, and Jedaizhongxin site in Baoding. The converted factor of OC to organic matter (OM) has been considered from 1.4 to 2.2, and it is related to atmospheric oxidation capacity and meteorology (Huang et al., 2017, 2020; Pang et al., 2020; Xu et al., 2019); this study adopted a factor of 1.6 because of high O$_3$ concentration and low temperature during the observed period.

![Fig. 2 – Characteristics of PM$_{2.5}$ at various sites in the Beijing-Tianjin-Hebei region.](image-url)
Beijing, Tianjin, and Baoding have similar characteristics of PM$_{2.5}$ concentration and chemical composition, and the mass concentration ratios of chemical compositions to PM$_{2.5}$ were 0.80, 0.75, and 1.03 in the above three cities, respectively (Table 1). The concentrations and chemical compositions of PM$_{2.5}$ in Baoding were consistent; however, Beijing and Tianjin have a large missing part. Trace elements in PM$_{2.5}$ were not detected, which can partly explain this phenomenon. Nevertheless, as shown in Section 2.1, there is a reversal between PM$_{2.5}$ and PM$_{10}$, and the uncertainty of PM$_{2.5}$ measurement could be another important reason.

### 2.2.1. OC and EC

The correlation coefficients ($R^2$) of OC and EC concentration are all greater than 0.87 among the three cities, which means that OC and EC had the same source. The concentration of total carbon (TC, the sum of OC and EC) was the lowest in Beijing, followed by Tianjin and the highest in Baoding. The TC of Beijing, Tianjin, and Baoding accounted for 9%, 17%, and 18% of PM$_{2.5}$, respectively, which was lower than that of similar cities (Li et al., 2019; Pang et al., 2020). This is closely related to the industrial layout in the BTH region (Xu et al., 2019). A lower proportion means a reduction in primary emissions intensity, and this phenomenon is closely related to the decrease of human activity level during the COVID-19 lockdown (Geng et al., 2019; Lv et al., 2020; Wang et al., 2019b).

The EC tracer method was widely used to estimate the photochemical contribution of secondary organic carbon (SOC) (Lim and Turpin, 2002; Zhang et al., 2021; Zheng et al., 2015). We estimated SOC by using the EC-tracer method, formulae as follows:

\[
POC = (\frac{OC}{EC})_{primary} \times EC
\]

\[
SOC = TOC - POC
\]

where POC is primary organic carbon, and TOC is the estimated total organic carbon. Data in the lowest 10% by OC/EC ratios were used to estimate the values of (OC/EC)$_{primary}$ (Appendix A Fig. S3). The analyzes show that SOC constituted 29%, 40%, 36% of TOC in Beijing, Tianjin, and Baoding. These values were slightly higher than the winter average, which is consistent with the haze episodes in the BTH region (Pang et al., 2020; Shao et al., 2018), indicating that POC was the main contributor to OC in all three cities, but the accumulation of SOC to OC increased during the heavy PM$_{2.5}$ pollution period.

### 2.2.2. Water-soluble ions

The average fractions of SNA (SO$_4^{2-}$, NO$_3^-$, NH$_4^+$) in PM$_{2.5}$ were 41%–73% in these three cities (Table 1). These values were higher than the winter average. Pang et al. (2020) has reported approximately 30%–40% in Beijing, Tianjin, and another city (Langfang) in the BTH region during the heating season. Previous studies have shown that the mass ratio of SNA to PM$_{2.5}$ was highest in the summer, about 45%–66%, due to strong photochemical reactions (Huang et al., 2017; Xu et al., 2019). In this study, the values of Beijing and Baoding were even higher than

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**Table 1 – Mass concentrations of PM$_{2.5}$ chemical compositions ($\mu$g/m$^3$) in Beijing, Tianjin, and Baoding.**

|          | Beijing | Tianjin | Baoding |
|----------|---------|---------|---------|
| OC       | 6.7±3.5 | 14.0±9.7| 17.1±12.1|
| EC       | 2.3±1.8 | 3.1±2.5 | 4.3±2.9 |
| SO$_4^{2-}$ | 16.7±9.6 | 11.9±8.6 | 33.6±24.9 |
| NO$_3^-$ | 33.4±24.0 | 14.5±12.1 | 31.5±26.9 |
| NH$_4^+$ | 15.9±8.8 | 14.7±9.0 | 22.3±16.0 |
| Cl$^-$   | 2.4±1.6 | 3.2±2.0 | 3.7±2.7 |
| Ca$^{2+}$| 0.0±0.0 | 0.1±0.1 | 0.3±0.4 |
| K$^+$    | 1.4±1.5 | 0.5±0.6 | 1.2±0.9 |
| Na$^+$   | 0.5±0.1 | 0.8±0.6 | 0.6±0.3 |
| Mg$^{2+}$ | 0.1±0.1 | 0.1±0.1 | 0.1±0.1 |
| F$^-$    | 0.1±0.1 | 0.1±0.1 | /       |
| SNA/PM$_{2.5}$ | 63%±16% | 41%±28% | 73%±21% |
| CC/PM$_{2.5}$ | 80%±17% | 75%±69% | 103%±23% |

SNA: SO$_4^{2-}$, NO$_3^-$ and NH$_4^+$; CC: chemical compositions.
the seasonal maximum, indicating that efficient secondary conversion ability during the COVID-19 lockdown.

The ratio of NO$_3^-$/PM$_{2.5}$ was the highest (32%) among the water-soluble ions in Beijing, followed by SO$_4^{2-}$ (16%) and NH$_4^+$ (15%). In Tianjin, the ratios of NO$_3^-$, SO$_4^{2-}$, NH$_4^+$ to PM$_{2.5}$ were similar, 15%, 15%, and 12%, respectively. In Baoding, the above three ratios were 28%, 26%, and 19%. Generally, the primary sources of NO$_3^-$, SO$_4^{2-}$, NH$_4^+$ were NO$_x$, SO$_2$, and NH$_3$, respectively (Seinfeld and Pandis, 2016). The BTH region is densely populated with heavy industries, such as steel, cement, and other heavy industry enterprises, with huge emissions of NO$_x$ and SO$_2$ (Geng et al., 2019; Zheng et al., 2018). Additionally, as a main grain-producing region in China, the southern part of the BTH region produces a large amount of NH$_3$ emission (Kang et al., 2016; Liu et al., 2019).

The ratio of NO$_3^-$/SO$_4^{2-}$ was generally used to judge the relative contributions of transportation and stationary sources (Arimoto et al., 1996; Pang et al., 2020). Beijing has the highest ratio of 2, and Baoding has the lowest value of 0.94. Comparatively, transportation sources in Beijing and stationary sources in Baoding contributed to PM$_{2.5}$ more significantly (Wang et al., 2014). The concentrations of SO$_4^{2-}$ and TC in Baoding were more than twice that of Beijing, but NO$_3^-$ concentration was similar. These phenomena reflected the transportation emissions intensity of the above three cities is similar, and the stationary sources emission of Baoding is more significant than Beijing and Tianjin.

2.2.3. Variations in different haze polluted conditions

We reclassified PM$_{2.5}$ polluted conditions into eight categories and analyzed the change characteristics of chemical compositions (Fig. 4a). There are various characteristics in different cities. For Beijing, with the increase of PM$_{2.5}$ concentration, the proportion of NO$_3^-$ raised rapidly. When the concentration of PM$_{2.5} > 200$ μg/m$^3$, the proportion of NO$_3^-$ could reach 46%. Pang et al. (2020) and Shao et al. (2018) reported that the proportion of NO$_3^-$ in PM$_{2.5}$ accounted for 20% and 16% on haze episodes during the 2016-2017 heating season. The result in this study is higher than that of previous studies, and NO$_3^-$ played a dominant position in promoting PM$_{2.5}$ concentration increase. In addition, the proportion of OM decreased with the increase of PM$_{2.5}$ concentration, and when PM$_{2.5}$ pollution was the most serious (>200 μg/m$^3$), the proportion of organic matter was the lowest, only 11%. The results show that during the PM$_{2.5}$ episodes in the COVID-19 lockdown, the direct contribution of primary source emissions to PM$_{2.5}$ was irrelevant in Beijing. For Tianjin, OM was in a major position, about 30%-40% of all chemical compositions. Furthermore, there is no significant change in the proportion of any major chemical compositions when the PM$_{2.5}$ concentration increased. The absolute concentrations of major chemical compositions have similarly increased rates with the increase of PM$_{2.5}$ concentration. For Baoding, NO$_3^-$ proportion raised gradually when PM$_{2.5}$ concentration increased, and the maximum ratio of NO$_3^-$ was 29%. This phenomenon is similar to the change in Beijing but not as evident. Besides, the trend of other major chemical compositions (OM, NH$_4^+$) was proportional to PM$_{2.5}$ concentration (similar to Tianjin).

Sulfur oxidation ratio (SOR) and nitrogen oxidation ratio (NOR) were used to evaluate the degree of conversion of SO$_2$ and NO$_x$ into secondary aerosols, calculated as a molar fraction using the following equations (Wang et al., 2005).

\[
\text{SOR} = \frac{n[\text{NSS} - \text{SO}_4^{2-}]}{n[\text{NSS} - \text{SO}_4^{2-}] + n[\text{SO}_2]} \tag{3}
\]

\[
\text{NOR} = \frac{n[\text{NO}_3^-]}{n[\text{NO}_3^-] + n[\text{NO}_2]} \tag{4}
\]

Here, $n$ refers to the molar concentration, and NSS refers to non-sea salt. NSS-SO$_4^{2-}$ was estimated with the following

Fig. 4 – Variations of (a) chemical compositions and (b) nitrogen oxidation ratio (NOR), sulfur oxidation ratio (SOR), RH, temperature as a function of PM$_{2.5}$ concentration in Beijing (up), Tianjin (middle), and Baoding (down).
equation in Tianjin (Pang et al., 2020).

\[ \text{NSS} - \text{SO}_4^{2-} = \left[ \text{SO}_4^{2-} \right] - 0.2455[\text{Na}^+] \] (5)

Beijing and Baoding are far away from the sea, and the influence of sea salt is not considered. We analyzed the distributions of SOR, NOR and meteorological factors (temperature, relative humidity) under various PM$_{2.5}$ polluted conditions (Fig. 4b). Overall, the SOR and NOR gradually increased with the increase of PM$_{2.5}$ concentration. In Beijing, the lowest SOR and NOR values were 0.07 and 0.02 in the condition of PM$_{2.5}$ was 0.15 μg/m$^3$. The highest SOR was 0.73, which was found in the PM$_{2.5}$ range was 76-100 μg/m$^3$, and the highest NOR was 0.33 when the PM$_{2.5}$ range was >200 μg/m$^3$; the maximum values of SOR and NOR did not occur in the same range of PM$_{2.5}$ concentrations. These phenomena show the various trends as the characteristics of chemical compositions of different PM$_{2.5}$ polluted conditions. The correlation coefficients (R) of SOR, NOR and PM$_{2.5}$ were 0.50 and 0.76. Both the trend and correlation between NOR and PM$_{2.5}$ were greater than SOR, indicating the enhanced secondary transformation of NO$_2$ to NO$_3^-$ is aggravated by increased PM$_{2.5}$ concentrations. In Tianjin, the trends of SOR, NOR, and PM$_{2.5}$ were similar to that of Beijing. The highest SOR and NOR values occurred when the PM$_{2.5}$ was at the range of 51-75 and >200 μg/m$^3$, respectively. The correlation coefficients of SOR, NOR and PM$_{2.5}$ were 0.67 and 0.68. When PM$_{2.5}$ concentration was higher than 100 μg/m$^3$, there was little difference for the proportion of SO$_4^{2-}$, but the percentage of NO$_3^-$ shows a decreasing trend with the increase of PM$_{2.5}$ concentration (Fig. 4a). The above phenomena indicate that the increase in PM$_{2.5}$ concentration could be affected by other factors. Further analysis results about chemical compositions of PM$_{2.5}$ in Tianjin found that OM accounts for the largest proportion in each category of PM$_{2.5}$ polluted conditions (Figs. 3 and 4a). The SOR and NOR of Baoding were different from those of Beijing and Tianjin. The correlation coefficients of SOR, NOR and PM$_{2.5}$ were 0.82 and 0.89, which were significantly higher than the other two cities. The maximum values of SOR and NOR occurred when the most serious PM$_{2.5}$ polluted condition, with 0.70 and 0.51, respectively. Compared with Beijing and Tianjin, the NOR of Baoding shows a rapid increase trend with PM$_{2.5}$ concentration increased.

2.3. Source apportionment of PM$_{2.5}$

2.3.1. Regional contribution

We used the WRF-CAMx model to distinguish the sources of pollutant transportation in the target cities, and the results showed that the local contribution to the PM$_{2.5}$ concentrations accounted for 28%, 40%, and 49% in Beijing, Tianjin, and Baoding, respectively (Fig. 5). This reflects the obvious inter-transport of PM$_{2.5}$ in the BTH region. Beijing was mainly affected by its eastern region; the contribution of TS, LC, and Tianjin to Beijing ranked the top three, with 12%, 10%, and 8%, respectively. Tianjin was mainly affected by its southern region; LC and SD contributed significantly to 12% and 11%. Baoding was mainly affected by its southern and western areas; SHXH and SX substantially contributed to Baoding, with 9% and 8%, respectively. The WRF-CAMx results of regional contributions are well in agreement with the ground-based meteorological monitoring data. According to the meteorological variable information, the dominant wind directions were east, south, and south in Beijing, Tianjin, and Baoding (Fig. 3). Additionally, the other regions also significantly impact the target cities, which means an increase in regional background PM$_{2.5}$ concentrations during this analysis period.

2.3.2. Contribution of pollution sources

The source apportionments of PM$_{2.5}$ in Beijing, Tianjin, and Baoding during this analysis period are shown in Fig. 6. From the entire region, industrial sources have a dominant contribution to the PM$_{2.5}$ concentration in Beijing, Tianjin, and Baoding with 39%, 37%, 40%, respectively, indicated that the current situation of high industrial emission intensity has not changed during the COVID-19 lockdown, and haze pollution is likely to occur in the event of unfavorable meteorological conditions (Cai et al., 2020).

Transportation is a major source of urban PM$_{2.5}$ concentration (http://sthjj.beijing.gov.cn/). Previous studies have shown that the contribution of transportation sources to PM$_{2.5}$ in Beijing was approximately 21%-43%, whereas Tianjin and Baoding was 17%-24% and 10%-14% (Gao et al., 2018; Xu et al., 2019; Zhang et al., 2019a). In this study, the contributions of transportation sources to PM$_{2.5}$ concentrations were significantly lower than the previously reported results, with 15%, 14%, 10% in Beijing, Tianjin, and Baoding cities, respectively; this is related to the regional control measures during the COVID-19 lockdown (Lv et al., 2020). The result is directly evidenced by road traffic flow data, which showed a 69% decrease in Hebei Province in February 2020 compared to February 2019 (Meng et al., 2021).

To better judge the contribution of different sources to PM$_{2.5}$ with varying levels of pollution, the results of daily source apportionments are shown in Appendix A Fig. S4. It was observed that the contribution of industrial and residential sources increased significantly with the increase of PM$_{2.5}$ concentration. On the heavy PM$_{2.5}$ pollution days of Beijing, Tianjin, and Baoding, the maximum daily contributions from industrial sources were 45%, 46%, 45%, respectively, and 22%, 27%, 34% from residential sources. In contrast, the contribution of mobile sources increased slightly, contributing up to 17% in the above three cities.

3. Conclusions

This study investigated the polluted characterization and evolution of PM$_{2.5}$ and its chemical compositions in Beijing, Tianjin, and Baoding cities of the BTH region during the COVID-19 lockdown (5-15 February 2020) and discussed the source apportionment of PM$_{2.5}$. The results showed that the maximum daily average PM$_{2.5}$ concentration reached the heavy pollution level (>150 μg/m$^3$) in the above three cities; for Beijing, the concentration was the highest value (207 μg/m$^3$) during the 2019-2020 heating season. The peak hourly PM$_{2.5}$ concentration at a site of the BTH region reached 330 μg/m$^3$, a value that was four times than the NAAQS II. The sum concentration of SO$_4^{2-}$, NO$_3^-$ and NH$_4^+$ played a dominant position in PM$_{2.5}$ chemical compositions of Beijing, Tianjin, and Baoding, which
means that secondary transformation of gaseous pollutants contributed significantly to the generation of PM$_{2.5}$; the SOR and NOR increased with the increase of PM$_{2.5}$ concentration, indicated secondary transformation was enhanced as the increased PM$_{2.5}$ concentration. WRF-CAMx simulations showed that the local contribution to the PM$_{2.5}$ concentrations did not exceed 50% in the above three cities, and obviously intertransport of PM$_{2.5}$ in the BTH region was found. Beijing, Tianjin, and Baoding were mainly affected by the eastern, southern, and southwest regions. The transportation source emissions were significantly reduced and lower than previous reports because of the regional control measures in the BTH region during the COVID-19 lockdown. However, the contribution of industrial and residential emission sources increased significantly with the increase of PM$_{2.5}$ concentration. The contribution of industrial emission sources was the largest, indicating that the status quo of high industrial emission intensity has not changed. The results highlight the importance of regional joint control strategies and industry emission reduction for mitigating haze pollution.

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Appendix A Supplementary data

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.jes.2021.08.030.

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