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Persistent high PM$_{2.5}$ pollution driven by unfavorable meteorological conditions during the COVID-19 lockdown period in the Beijing-Tianjin-Hebei region, China

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**ABSTRACT**

Lockdown measures to curtail the COVID-19 pandemic in China halted most non-essential activities on January 23, 2020. Despite significant reductions in anthropogenic emissions, the Beijing-Tianjin-Hebei (BTH) region still experienced high air pollution concentrations. Employing two emissions reduction scenarios, the Community Multiscale Air Quality (CMAQ) model was used to investigate the PM$_{2.5}$ concentrations change in this region. The model using the scenario (C3) with greater traffic reductions performed better compared to the observed PM$_{2.5}$. Compared with the no reductions base-case (scenario C1), PM$_{2.5}$ reductions with scenario C3 were 2.70, 2.53, 2.90, 2.98, 3.30, 2.81, 2.82, 2.98, 2.68, and 2.83 $\mu g/m^3$ in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Hengshui, Tangshan, and Xingtai, respectively. During high-pollution days in scenario C3, the percentage reductions in PM$_{2.5}$ concentrations in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Hengshui, Tangshan, and Xingtai were 3.76, 3.54, 3.28, 3.22, 3.57, 3.56, 3.47, 6.10, 3.61, and 3.67%, respectively. However, significant increases caused by unfavorable meteorological conditions counteracted the emissions reduction effects resulting in high air pollution in BTH region during the lockdown period. This study shows that effective air pollution control strategies incorporating these results are urgently required in BTH to avoid severe pollution.

1. Introduction

Towards the end of December 2019, an infectious disease that was later linked to the family of coronaviruses broke out in Wuhan, the capital city of Hubei province, China (Sulaymon et al., 2021). A cluster of coronavirus 2019 (COVID-19) cases was confirmed in Wuhan by the Chinese authority in January 2020. However, within a short time, it spread to the neighboring cities in Hubei province and beyond. To limit the spread of the pandemic, a nationwide lockdown was announced by the Chinese government on January 23, 2020. Despite significant reductions in anthropogenic emissions, the Beijing-Tianjin-Hebei (BTH) region still experienced high air pollution concentrations. Employing two emissions reduction scenarios, the Community Multiscale Air Quality (CMAQ) model was used to investigate the PM$_{2.5}$ concentrations change in this region. The model using the scenario (C3) with greater traffic reductions performed better compared to the observed PM$_{2.5}$.

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2018, 2021). Also, high concentrations of PM$_{2.5}$ pose adverse health effects on human health (Global Burden of Disease GBD, 2020; U.S. Environmental Protection Agency USEPA, 2019). Annually, about 4.2 million people die prematurely due to exposure to air pollution (Ambient air pollution, 2021).

The important roles being played by the meteorological variables (wind speed, temperature, relative humidity, and planetary boundary layer height) in the formation, transportation, diffusion, and deposition of air pollutants cannot be overemphasized (Hu et al., 2016; Shi et al., 2020; Sulaymon et al., 2020, 2021; Wang et al., 2020b) as unfavorable meteorological conditions exacerbate high pollution. Such high pollution conditions are more frequent in winter even with limited reductions in anthropogenic emissions (Chen et al., 2020b; Fu et al., 2020; Liu et al., 2020; Shi et al., 2020; Wang et al., 2020b; Yang et al., 2019). In terms of its economy, industrialization, urbanization, and population growth, the Beijing-Tianjin-Hebei (BTH) region is one of the most developed regions in China. In recent decades, persistent high air pollution has been reported in the region (Chang et al., 2018, 2019; Zhao et al., 2019) especially during the winter period due to unfavorable meteorological conditions. During international events such as Beijing Olympic Games 2008, APEC Summit 2014, and the Military Parade 2015, several air pollution control policies were enacted by the Chinese authorities as a way of improving the air quality in the BTH region. Previous studies have documented the effectiveness of the emission control policies during the events in BTH region (Cheng et al., 2016; Wang et al., 2016; Wu et al., 2016; Xu et al., 2017; Yang et al., 2016; Zhao et al., 2016a, 2016b). However, the duration of these control periods was short and the measures were not strict compared to this year’s prolonged COVID-19 lockdown with very strict measures in BTH region and China as a country. To the best of our knowledge, this is the first study to evaluate the contributions of emissions reductions and meteorological conditions to PM$_{2.5}$ concentrations before and during the COVID-19 pandemic lockdown periods in the 10 major cities of BTH region using chemical transport model. Hence, this study provides an assessment of these measures across multiple cities and can provide information to guide future control planning.

This study investigated and quantified the contributions of anthropogenic emission reductions due to COVID-19 lockdown along with the impacts of meteorological conditions on air quality in the BTH region. Three different emission scenarios were formulated and simulated using the Community Multiscale Air Quality (CMAQ) model to investigate why the region was still characterized with several high-pollution days despite the lockdown being in place.

2. Materials and methods

The Community Multiscale Air Quality (CMAQ V5.2) model was used to simulate air quality in the Beijing-Tianjin-Hebei (BTH) region. The model was configured with SAPRC07tc photochemical mechanism and the AER06i aerosol module (Fu et al., 2020; Liu et al., 2020). A one-way, triple nested domain was used. The first domain (36 km horizontal resolution) covers China mainland and part of East and Southeast Asia; the second domain (12 km horizontal resolution) covers eastern China, while the innermost domain (4 km horizontal resolution) covers the study area (the BTH region). Default profiles provided by the CMAQ model were used as the initial and boundary conditions of the first domain while the results of the outer domains served as the initial and boundary conditions for the subsequent inner domains. The simulation began on December 27, 2019 and ended on February 29, 2020. In order to minimize the impact of initial conditions, the results of the first five days (spin-up) were not included in the analysis. Two simulation periods were defined: pre-lockdown (January 1st to January 22nd) and lockdown (January 23rd to February 29th). The meteorological fields were simulated with the Weather Research and Forecasting (WRF v4.0) model. Detailed configurations of WRF model adopted in this study have been described in previous related studies (Hu et al., 2015a, 2016; Zhang et al., 2012).

To provide the anthropogenic emissions from China, the Multi-resolution Emission Inventory for China (MEIC) of year 2016 with resolution of 0.25° × 0.25° (http://www.meicmodel.org) was used. For other countries in the domain, emissions from the gridded Regional Emission inventory in Asia, version 2 (REAS2) with resolution of 0.25° × 0.25° were used (Kurokawa et al., 2013). Biogenic emissions were generated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN v2.1). For biomass burning emissions, the Fire INventory from NCAR (FINN) (Wiedinmyer et al., 2011) was used. During the CMAQ simulations, sea salt and windblown emissions were generated inline. Detailed descriptions of the emission processing are provided in Hu et al. (2016) and Qiao et al. (2015).

To quantify the impacts of the reduction in anthropogenic emission on ambient air quality, three scenarios were simulated for comparison (Table 1). For the base case scenario (C1), the original anthropogenic emission inventory (MEIC16) was used throughout the whole simulation period. In scenario 2 (C2), a reduction in industry scaled with a factor of 0.80 and transportation with a scaling factor of 0.80 was implemented while the emissions from residential sources was adjusted by scaling factor of 1.10 since people were required to be at home. Emissions from agriculture were set to be the same as C1. For the third simulation scenario (C3), transportation emissions were scaled by factor of 0.20 while the remaining emission sources were those in C2. The emissions from power plants were held constant in the 3 scenarios since there was little change in the demand for electricity. Even though there was slight reduction in industrial activities during the lockdown period, the stay-at-home orders that were in place led to possibly higher demand and consumption of power for home heating and lighting since the lockdown period was in winter. In the absence of official emission inventory during the lockdown, the emission scaling factors used in this study followed the suggestions by the Chinese Research Academy of Environmental Sciences (CRAES, 2020) regarding the status of emission inventory during the lockdown and were also consistent with those of Wang et al. (2020a).

To investigate the effects caused by the changes in anthropogenic emissions, the difference between the concentrations in C3 and C1 was designated as the impact of the emissions reductions attributed to the COVID-19 lockdown since the same meteorology was used for the two simulations. The difference in pollutant concentrations between high-pollution days and low-pollution days in C3 during the lockdown was considered as the effects of changes in meteorology.

3. Results and discussion

3.1. Model validation

3.1.1. WRF model performance

The significant role played by the meteorological variables in the formation, transportation, diffusion, and deposition of air pollutants has been documented in previous studies (Hu et al., 2015a, 2016). Measured data were downloaded from the National Climate Data Center (NCDC). The data were used for the validation of WRF performance, including relative humidity (RH) and temperature (T2) at 2 m above surface, and wind speed (WS) and wind direction (WD) at 10 m above the ground level. The statistical results of the model performance are shown in Table 2 and include mean observation (OBS), mean prediction (PRE), mean bias (MB), gross error (GE), as well as the root mean square error.

| Scenario ID | Residential | Transportation | Power | Industry | Agriculture |
|-------------|-------------|----------------|-------|----------|-------------|
| C1          | 1.00        | 1.00           | 1.00  | 1.00     | 1.00        |
| C2          | 1.10        | 0.60           | 1.00  | 0.80     | 1.00        |
| C3          | 1.00        | 0.20           | 1.00  | 0.80     | 1.00        |
RMSE is root mean square error). The values that do not meet the criteria are highlighted in bold.

Table 2
Meteorology performance during January 01 to February 29, 2020 (OBS means observation; PRE means prediction; MB means mean bias; GE means gross error; RMSE is root mean square error). The values that do not meet the criteria are highlighted in bold.

| Parameters | Indices       | Jan 01-Feb 29, 2020 | Benchmark
|------------|---------------|---------------------|----------------
| T2(K)      | OBS           | 272.6               | ≤±0.5
|            | PRE MB        | 275.8               | ≤2.0
|            | GE            | 3.1                 | 4.8
|            | RMSE          | 3.8                 | 2.0
| WS10(ms/s) | OBS           | 2.0                 | ≤±0.5
|            | PRE MB        | 3.3                 | ≤2.0
|            | GE            | 1.2                 | ≤2.0
|            | RMSE          | 1.4                 | 1.8
| WD10(°)   | OBS           | 178.1               | ≤±10
|            | PRE MB        | 177.3               | ≤±30
|            | GE            | 0.7                 | 46.8
|            | RMSE          | 64.8                | 16.1
| RH2(%)     | OBS           | 64.0                | 41.30
|            | PRE MB        | 59.1                | 91.23
|            | GE            | -4.9                | 144.47
|            | RMSE          | 12.7                | 140.16

* The benchmarks used were suggested by Emery et al. (2001).

(RMSE). The benchmarks used in this study were suggested by Emery et al. (2001). The WRF model slightly over-predicted WS (Fig. S1) with positive MB value of 1.2, which is beyond the benchmark. However, the GE and RMSE values of WS are within the benchmarks. With the MB value of −0.7, WD (Fig. S2) meets the benchmark of ≤±10° and the result is acceptable. GE value of WD was above the benchmark by 56%. T2 (Fig. S3) had an MB value of 3.1, indicating a slight over-estimation compared to the observations. The GE value of T2 was higher than the benchmark by 90%. RH (Fig. S4) was under-estimated with MB value of −4.9. Generally, air pollutants’ concentrations are associated with meteorological parameters especially in highly polluted areas in China (Shi et al., 2020; Wang et al., 2014). Also, bias in simulated meteorological variables largely contributes to bias in the predicted PM2.5 concentrations (Hu et al., 2015b; Shi et al., 2020). The performance of WRF model in this study is comparable to other previous studies in BTH region (Chang et al., 2018; Zhang et al., 2018, 2019) and China as a whole (Fu et al., 2020; Hu et al., 2016; Qiao et al., 2018, 2019; Wang et al., 2020b; Zhang et al., 2012).

3.1.2. PM2.5 model performance

Ten major cities (Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Hengshui, Tangshan, and Xingtai) in BTH region were selected for analyses. The hourly PM2.5 observation data from the air quality monitoring stations in the cities were downloaded from the China’s National Environmental Monitoring Center (http://www.cnemc.cn). Validation and necessary quality checks of the data followed the approach of Sulaymon et al. (2021). To identify the model performance in different cities of BTH region, model validations were performed separately for each city.

PM2.5 model performance in different cities and periods are shown in Table 3 (C3) while those of C1 and C2 are in the Supplementary Material. The mean observations (OBS), mean predictions (PRE), mean fractional bias (MFB), mean fractional error (MFE), mean normalized bias (MNB), and mean normalized error (MNE) were estimated. The predicted and observed daily PM2.5 in C1, C2, and C3 in the ten major cities of BTH are illustrated in the Supplementary Material, while the predicted daily PM2.5 major components with observed daily PM2.5 in the cities in C1, C2, and C3 are shown in the Supplementary Material. In C1, PM2.5 was well predicted in all cities before lockdown except Hengshui with an MFB (0.63) above the criterion suggested by EPA (2007) while the model performance statistics of MFB fell within the EPA criterion for all cities during the lockdown period. MFE values for all cities during the two periods were within the EPA criterion value of ≤±0.75. In addition, prior to lockdown period, negative MFB values were obtained for all cities except Beijing, Cangzhou, and Hengshui, indicating the model under-predicted the PM2.5 concentrations. A similar situation was obtained during the lockdown in all cities except Hengshui.

Generally, the predicted PM2.5 concentrations agreed well with observations, with the model performance statistics meeting the suggested criteria in all the cities, scenarios, and periods except Hengshui in C1 and C2 before the lockdown period. However, relatively large bias in model predicted concentrations were found in some cities especially before lockdown period. Model bias is mainly attributed to uncertainties associated with meteorological fields, emission inventory, model treatment, and configurations. Further studies are still needed to continue improving the model capability in accurately predicting air quality in China. In comparison with the predicted PM2.5 concentrations in C1 and C2, the simulated results in C3 were better since significant reductions in PM2.5 concentrations in all the cities before and during the lockdown periods were captured. Due to the shutting down of major sectors (public transportation systems, schools, business centers, parks, non-essential industries, restaurants, and entertainment houses) during the lockdown period, which led to reductions in anthropogenic emissions (Sulaymon et al., 2021), the results of scenario C3 had better predictions and were used in further discussion.

Table 3
Model performance of PM2.5 in C3 before and during the lockdown (OBS is mean observation; PRE is mean prediction; MFB is mean fractional bias; MFE is mean fractional error; MNB is mean normalized bias; MNE is mean normalized error). The performance criteria for PM2.5 were suggested by EPA (2007). The values that do not meet the criteria are highlighted in bold.

| Before | Beijing     | Tianjin     | Shijiazhuang | Baoding  | Cangzhou  | Chengde  | Handan   | Hengshui  | Tangshan  | Xingtai   | Criteria |
|--------|-------------|-------------|--------------|----------|-----------|----------|----------|-----------|-----------|-----------|----------|
| PM2.5 (µg/m³) | OBS        | 41.30       | 91.23        | 144.47   | 106.91    | 61.44    | 108.39   | 140.16    | 28.71     | 80.53     | 138.22   |
|         | PRE         | 57.28       | 51.25        | 68.24    | 62.95     | 62.60    | 54.92    | 66.26     | 69.08     | 55.81     | 65.16    |
|         | MFB         | 0.31        | -0.21        | -0.41    | -0.30     | 0.13     | -0.38    | -0.42     | 0.57      | -0.22     | -0.43    |
|         | MFE         | 0.48        | 0.43         | 0.46     | 0.33      | 0.37     | 0.38     | 0.44      | 0.65      | 0.32      | 0.45     |
|         | MNB         | 0.86        | -0.14        | -0.47    | -0.36     | 0.41     | -0.46    | -0.48     | 1.61      | -0.23     | -0.49    |
|         | MNE         | 1.07        | 0.62         | 0.55     | 0.41      | 0.71     | 0.46     | 0.52      | 1.71      | 0.42      | 0.53     |
| During | Beijing     | Tianjin     | Shijiazhuang | Baoding  | Cangzhou  | Chengde  | Handan   | Hengshui  | Tangshan  | Xingtai   | Criteria |
| PM2.5 (µg/m³) | OBS        | 72.75       | 78.13        | 100.28   | 106.89    | 82.21    | 70.58    | 86.62     | 39.76     | 82.64     | 85.51    |
|         | PRE         | 49.28       | 47.56        | 55.44    | 56.33     | 56.02    | 48.10    | 55.16     | 56.39     | 49.14     | 54.10    |
|         | MFB         | 0.05        | -0.16        | -0.28    | -0.25     | -0.08    | -0.19    | -0.22     | 0.24      | -0.24     | -0.23    |
|         | MFE         | 0.44        | 0.22         | 0.36     | 0.22      | 0.34     | 0.26     | 0.32      | 0.38      | 0.30      | 0.34     |
|         | MNB         | 0.25        | -0.10        | -0.27    | -0.23     | 0.09     | -0.18    | -0.20     | 0.82      | -0.24     | -0.20    |
|         | MNE         | 0.83        | 0.48         | 0.49     | 0.45      | 0.58     | 0.36     | 0.45      | 1.00      | 0.41      | 0.49     |
3.2. Impacts of emission reductions on PM$_{2.5}$ in different cities

The average predicted concentrations of PM$_{2.5}$ major components and observed PM$_{2.5}$ concentrations in the selected ten major cities under the three scenarios during the lockdown period are illustrated in Fig. 1.

The reduction in the anthropogenic emissions in C3 did not cause significant reduction in PM$_{2.5}$ major components’ concentrations across the cities. The highest reduction was recorded in Cangzhou (−3.00 µg/m$^3$) while the lowest was found in Tianjin (−2.35 µg/m$^3$). The reductions in PM$_{2.5}$ major components’ concentrations in C3 when compared with C1

![Figure 1](image-url)
were $-2.50, -2.66, -2.73, -2.74, -2.60, -2.73, -2.51,$ and $-2.57 \, \mu g/m^3$ in Beijing, Shijiazhuang, Baoding, Chengde, Handan, Hengshui, Tangshan, and Xingtai, respectively. Fig. 2 shows the spatial variations of the changes of simulated PM$_{2.5}$ between the base case (C1) and the two emission reduction scenarios (C2 and C3) during the lockdown period. When compared to C1, PM$_{2.5}$ increased by up to 10 $\mu g/m^3$ in C2. This rise could be attributed to the increase in residential combustion sources (10%) in C2 as people were mandated to stay at home during the lockdown period. The spatial changes of PM$_{2.5}$ concentrations, which increased by up to 20 $\mu g/m^3$ in C2 before the lockdown period are illustrated in Fig. S15 in the Supplementary Material.

The averaged predicted daily PM$_{2.5}$ with its major components and observed PM$_{2.5}$ concentrations in the ten major cities under study during the high-pollution and clean (low-pollution) days are displayed in Fig. 3. According to the second level of Chinese NAAQS, high-pollution days are defined by daily PM$_{2.5}$ concentrations above 75 $\mu g/m^3$. During the lockdown period, the reductions in PM$_{2.5}$ concentrations during high-pollution days in C3 when compared with C1 in Beijing, Tianjin, Shijiazhuang, Baoding, Chengde, Handan, Hengshui, Tangshan, and Xingtai were 3.72, 4.27, 3.47, 3.92, 4.40, 3.98, 3.76, 9.03, 4.50, and 3.74 $\mu g/m^3$, respectively. Overall, the changes were below 10%. Hengshui had the highest reduction of 6.10%. For other cities, the percentage reductions were 3.76, 3.54, 3.28, 3.22, 3.57, 3.47, 3.61, and 3.67% in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Tangshan, and Xingtai, respectively. The percentage of high polluted days was highest in Shijiazhuang (64.9%) followed by Xingtai (56.8%) and the lowest was traced to Hengshui (10.8%).

Alternatively, during low-pollution days, the reductions were 1.80, 0.72, 1.20, 1.53, 1.84, 1.91, 1.41, 1.97, 0.66, and 1.10 $\mu g/m^3$ in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Hengshui, Tangshan, and Xingtai, respectively. The reductions were less than 5% across the cities and the highest was found in Chengde (2.91%) while the lowest was observed in Tangshan (1.35%). For the low-pollution days, Hengshui had the highest percentage of clean days with 89.2%, followed by Beijing (62.2%) and the lowest was recorded in Shijiazhuang (35.1%).

The benefits of emission reductions were counteracted by unfavorable meteorological conditions resulting in high PM$_{2.5}$ pollution. Thus, this study showed that substantive reductions in transportation emissions and slight reductions in industrial emissions could not guarantee improved air quality in BTH region when unfavorable weather conditions occur. This study has also showed that the relationships between emissions and concentrations are not usually linear (Xing et al., 2020). Understanding and including the roles of both chemistry and meteorology in the formation of air pollutants is important as illustrated in this study. It is also important to use multi-pollutant nonlinear response models when designing effective emission control strategies as suggested by Xing et al. (2020).

3.3. Relative changes due to emission reductions

Fig. 4 shows the relative changes of major PM$_{2.5}$ components between C3 and C1 across the ten cities. Significant reductions were found in nitrate (NO$_3^-$), elemental carbon (EC), and ammonium (NH$_4^+$) while the changes in sulfate (SO$_4^{2-}$) and primary organic aerosols (POA) were below 10% in all the cities. For instance, in Chengde where the highest reductions were observed, the concentrations of NO$_3^-$, EC, NH$_4^+$, SO$_4^{2-}$, and POA decreased by 24.2, 22.6, 15.0, 9.0, and 4.3%, respectively. Other cities followed the same trends. Alternatively, the concentrations of secondary organic aerosols (SOA) and the group of compounds labelled as OTHER increased (rather than decreases) even though these increases were <3% across the cities.

Fig. S16 presents the changes in PM$_{2.5}$ major components before and during the lockdown in C3. In Tianjin, Baoding, Cangzhou, and Chengde. All the chemical species except SO$_4^{2-}$ and SOA decreased during the lockdown compared to their concentrations before the lockdown. There were reductions in the concentrations of all the species in the remaining six cities. Comparing the two periods (before

Fig. 2. Spatial distributions of predicted PM$_{2.5}$ and the changes between the base case (C1) and the two emission reduction scenarios (C2 and C3) during the lockdown period. Units are in $\mu g/m^3$. 

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Fig. 3. Average predicted daily PM$_{2.5}$ with major components and observed PM$_{2.5}$ in the 10 major cities under the three scenarios on high-pollution days and low-pollution days during the lockdown. The number of days in high (H) and low (L) pollution days are indicated after the city names. Units are in μg/m$^3$.
and during the lockdown), significant reductions were found in NO$_3^-$, POA, EC, and NH$_4^+$ while the changes in SO$_4^{2-}$ and SOA were less than 10% in all the cities. The highest reduction of NO$_3^-$ was observed in Chengde (−40.6%) while Shijiazhuang had the highest reductions of POA (−34.79%), EC (−31.69%), and NH$_4^+$ (−24.17%). The substantial reductions in NO$_3^-$ during the lockdown period could be attributed to reduction in its precursors (NO$_x$) due to drastic reduction in vehicular movement and suspension of public transport across the country. The reduction in NH$_4^+$ could also be due to reduction in light-duty vehicles with catalytic converters (Heeb et al., 2006; Zhou et al., 2019).

3.4. Impacts on PM$_{2.5}$ of emissions from festival activities

During the spring festival, intensive fireworks are usually displayed
beginning on the eve of the Chinese New year. The Chinese New year began on January 25, 2020, while the Lantern festival was celebrated on February 8, 2020. In addition to this, there is an annual traditional event in the northern part of China called “Sheng Wang Huo” that is usually celebrated during the spring festival. As a way of celebrating Sheng Wang Huo annual event, a large pillar of wood and coal is usually ignited on New Year’s Eve and burnt for about five days. Also, during the Lantern festival and other major cultural events, burning of wood and coal is a norm for the Chinese people. Although, the Chinese authorities at local government levels had banned this event as a way of reducing its impact on ambient air quality, a recent study by Dai et al. (2020) revealed that the people in the rural areas of provinces such as Hebei, Shanxi, and Inner Mongolia still observed Sheng Wang Huo during this year’s Spring and Lantern Festivals. The atmospheric residence time of particulate matter from fireworks is around four days (Dai et al., 2020).

The significant contributions due to fireworks and coal/wood burning were observed as higher PM$_{2.5}$ pollution occurred starting from January 24 and lasted till January 31 in the cities except Hengshui where no record of high pollution was observed during the spring festival. For instance, the ranges of PM$_{2.5}$ concentrations between January 24 to January 31 in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Tangshan, and Xingtai were 76.29–169.67, 85.08–237.00, 129.38–206.58, 92.29–377.38, 80.75–247.29, 80.71–184.29, 100.25–157.25, 78.08–243.00, and 95.38–151.63 μg/m$^3$, respectively. Also, during the Lantern festival, the contributions attributed to fireworks and coal/wood burning were significant and lasted until February 13 across the cities. Between February 7 and February 13, the ranges of PM$_{2.5}$ concentrations were 119.83–205.67, 97.42–169.79, 103.13–213.17, 105.17–199.38, 82.46–194.82, 76.54–127.50, 77.50–167.63, 84.83–95.67, 75.75–190.71, and 90.13–170.5 μg/m$^3$ in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Chengde, Handan, Hengshui, Tangshan, and Xingtai, respectively. The continuous high-pollution days recorded during the two festival periods could be attributed to the emissions from fireworks, coal/wood burning, and residential burning and were driven by poor meteorological conditions.

3.5. Impacts of meteorological conditions

As a result of reduction in anthropogenic emissions in C3, reduction in the concentrations of PM$_{2.5}$ were noticed across the ten cities of BTH region, though very low. As discussed earlier and shown in Fig. 3, high pollution persisted in all the cities except Hengshui despite reductions in anthropogenic activities during the lockdown period. It can be inferred that meteorological conditions such as low wind speed, high relative humidity, high temperatures, and low planetary boundary layer heights favored stagnation rather than ventilation, and enhanced the higher pollution formation especially during the festival periods as discussed in section 3.4. During the simulation period, there were high temperatures (Fig. S3), high relative humidity (Fig. S4), low wind speeds (Fig. S1), and low PBLHs (Fig. S5) across the cities in BTH region. The formation of secondary particulate matter was enhanced by these higher temperatures and RH (Li et al., 2019; Wang et al., 2019, 2020c, 2020c; Wu et al., 2019; Zhang et al., 2020) because reaction rates are higher without the temperatures reaching values that favor dissociation of the ammonium nitrate given that the mean temperature for the study period was ~0°C. Alternatively, the dispersion of atmospheric pollutants was hindered by low wind speed and lower planetary boundary layer height (Li et al., 2019; Liu et al., 2017; Wang et al., 2020b).

The efficiency of atmospheric disperse of was evaluated using the ventilation coefficient (VC). VC is the product of the wind speed times the mixed layer height and is reported in m$^2$/s. Details of the VC can be found in Dai et al. (2020) and Tiwari et al. (2019). Due to poor dispersion, low VC values are seen for higher pollutant concentrations at a fixed emission rate. Fig. 5 shows the time series of PM$_{2.5}$ concentrations and VC for Beijing, Tianjin, and Shijiazhuang while Figs S17 and S18 in the Supplementary Material show the time series for other cities. Lower values of VC led to high PM$_{2.5}$ concentrations across the cities and subsequently resulted to several high-pollution days especially during the festival periods and up to six days after the festivals. Days with very low VC values had correspondingly high pollutant concentrations.

The changes due to meteorological conditions and reduction of anthropogenic emissions were calculated and illustrated in Fig. 6. Reduction in emissions caused reductions in PM$_{2.5}$ in all the cities. The changes were very small and less than 5 μg/m$^3$ across the cities. Cangzhou (−3.30 μg/m$^3$) had the highest and the lowest was observed in Tianjin (−2.53 μg/m$^3$). The changes in other cities were −2.70, −2.90, −2.98, −2.81, −2.82, −2.98, −2.68, and −2.83 μg/m$^3$ in Beijing, Shijiazhuang, Baoding, Chengde, Handan, Hengshui, Tangshan, and Xingtai, respectively. Alternatively, substantive but opposite changes were observed for PM$_{2.5}$ due to unfavorable meteorological conditions during the COVID-19 lockdown period. This situation led to increments in PM$_{2.5}$ concentration across the cities. Tangshan had the highest contribution of 72 μg/m$^3$, followed by Tianjin (66 μg/m$^3$) while the lowest was found in Xingtai (19 μg/m$^3$). Clearly, in all the ten cities, the
significant increment caused by unfavorable meteorological conditions had counteracted the very low positive effects linked to emission reductions. Thus, severe high pollution occurred in BTH region during the COVID-19 lockdown period.

4. Conclusions

This study investigated the impacts of emission reductions and changes in meteorological conditions on PM$_{2.5}$ concentrations during the COVID-19 lockdown in BTH region. The reductions in anthropogenic emissions led to decreased PM$_{2.5}$ concentrations across the cities. The reduction in predicted PM$_{2.5}$ concentrations were 2.70, 2.53, 2.90, 2.98, 3.30, 2.81, 2.82, 2.98, 2.68, and 2.83 μg/m$^3$ in Beijing, Tianjin, Shijiazhuang, Baoding, Cangzhou, Handan, Hengshui, Tangshan, and Xingtai, respectively. Across the cities, the levels of PM$_{2.5}$ showed the opposite trend due to unfavorable meteorological conditions during the lockdown period. Tangshan had the highest contribution of 72 μg/m$^3$, followed by Tianjin (66 μg/m$^3$) while the lowest was found in Xingtai (19 μg/m$^3$). During the lockdown, the percentage of days with high pollution was 64.9% in Shijiazhuang, followed by Xingtai (56.8%) and the lowest was observed in Hengshui (10.8%). Obviously, in all the ten cities, the significant increment caused by unfavorable meteorological conditions had counteracted the very low positive effects attributed to emission reductions. Thus, high air pollution occurred in BTH region during the lockdown period. In designing effective emission control strategies to reduce PM$_{2.5}$ level in BTH region, it is pertinent to understand and take into consideration the significant roles that both chemistry and meteorology play in the formation of air pollutants as highlighted in this study.

Credit author contribution statement

Ishaq Dimeji Sulaymon: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing - original draft, Writing - review & editing. Yuaxun Zhang: Conceptualization, Supervision, Funding acquisition, Writing - review & editing. Philip K. Hopke: Conceptualization, Data curation, Formal analysis, Writing - review & editing. Jianlin Hu: Conceptualization, Writing - review & editing. Yang Zhang: Writing - review & editing. Lin Li: Data curation, Formal analysis. Xiaodong Mei: Data curation, Formal analysis. Kangjia Gong: Data curation, Formal analysis. Zhihao Shi: Data curation, Formal analysis. Bin Zhao: Writing - review & editing. Fangxin Zhao: Data curation.

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.envres.2021.11186.

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