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Impacts of COVID-19 on air quality in mid-eastern China: An insight into meteorology and emissions

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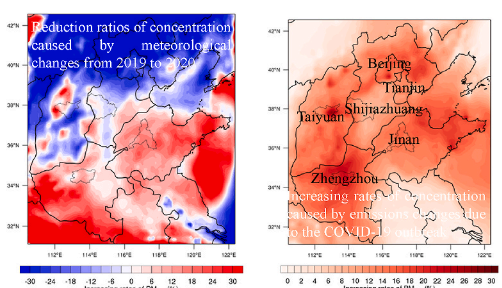
HIGHLIGHTS

- Polluted days account for 31.6%–60.5% during COVID-19 although emission decreased.
- Air quality improved if a COVID-19 outbreak in 2019 instead of 2020.
- $PM_{2.5}$ concentrations increased by 10.9%–20.5% without COVID-19 outbreak in 2020.
- Industry and residential use were the dominant $PM_{2.5}$ contributors during COVID-19.

GRAPHICAL ABSTRACT



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ABSTRACT

The coronavirus disease (COVID-19) spread rapidly worldwide in the first half of 2020. Stringent national lockdown policies imposed by China to prevent the spread of the virus reduced anthropogenic emissions and improved air quality. A weather research and forecasting model coupled with chemistry was applied to evaluate the impact of meteorology and emissions on air quality during the COVID-19 outbreak (from January 23 to February 29, 2020) in mid-eastern China. The results show that air pollution episodes still occurred on polluted days and accounted for 31.6%–60.5% of the total number of outbreak days in mid-eastern China from January 23 to February 29, 2020. However, anthropogenic emissions decreased significantly, indicating that anthropogenic emission reduction cannot completely offset the impact of unfavorable meteorological conditions on air quality. Favorable meteorological conditions in 2019 improved the overall air quality for a COVID-19 outbreak in 2019 instead of 2020. $PM_{2.5}$ concentrations decreased by 4.2%–29.2% in Beijing, Tianjin, Shijiazhuang, and Taiyuan, and increased by 6.1%–11.5% in Jinan and Zhengzhou. $PM_{2.5}$ concentrations increased by 10.9%–20.5% without the COVID-19 outbreak of 2020 in mid-eastern China, and the frequency of polluted days increased by 5.3%–18.4%. Source apportionment of $PM_{2.5}$ during the COVID-19 outbreak showed that industry and residential emissions were the dominant $PM_{2.5}$ contributors (32.7%–49.6% and 26.0%–44.5%, respectively) followed by agriculture (18.7%–24.0%), transportation (7.7%–15.5%), and power (4.1%–5.9%). In Beijing, industrial and residential contributions to $PM_{2.5}$ concentrations were lower (32.7%) and higher (44.5%), respectively, than in

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other cities (38.7%–49.6% for industry and 26.0%–36.2% for residential). Therefore, enhancing regional cooperation and implementing a united air pollution control are effective emission mitigation measures for future air quality improvement, especially the development of new technologies for industrial and cooking fumes.

1. Introduction

Overall air quality in China improved during the COVID-19 outbreak owing to unconventional measures (e.g., social distancing and the suspension of public transport) implemented on January 23, 2020 in Wuhan, Hubei Province, to prevent the spread of the virus (Chen et al., 2020; Chu et al., 2020; Xu et al., 2020). Compared to 2019 levels, the national particulate matter ($PM_{2.5}$ and PM_{10}, with aerodynamic diameters <2.5 μm and 10 μm, respectively), SO_2, CO, and NO_2 concentrations decreased by 8%–17% from January to May 2020; however, O_3 increased by 12% (Nie et al., 2021).

Meteorological conditions play a non-negligible role in air quality variation (Chen et al., 2021; Fan et al., 2021; Shen et al., 2021; Zhai et al., 2019). Weather research and forecasting models coupled with chemistry (WRF/Chem) and community multiscale air quality (CMAQ) have been extensively applied to evaluate the contribution of inter-annual meteorological changes to air pollutant concentration reductions (Jiang et al., 2021; Sulaymon et al., 2021; Zhang et al., 2020). For example, Xiao et al. (2021) revealed the dominant role of emission changes in the long-term trend of $PM_{2.5}$ concentrations in China from 2000 to 2018 and the significant influence of meteorological conditions. Zhang et al. (2019) reported that meteorological conditions played an important role in decreasing winter $PM_{2.5}$ concentrations in the Yangtze River Delta (YRD) and the Beijing-Tianjin-Hebei (BTH) regions. Our previous study found that the inter-annual meteorological changes contributed 3.4%–18.6% to reductions in $PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2 concentrations in Shandong province from 2015 to 2019; however, these changes had little impact on O_3 when compared with 2013 levels (Zhao et al., 2021b). In addition, severe air pollution events with daily $PM_{2.5}$ concentrations >200 μg/m^3 occurred during the COVID-19 outbreak due to unfavorable meteorological conditions; however, anthropogenic emissions decreased (Li et al., 2021; Wang et al., 2020b; Zhao et al., 2020). Xian et al. (2021) found that high humidity and low wind speed favor haze formation and that unprecedented emission reductions improved air quality. Therefore, evaluating the impacts of meteorological changes on $PM_{2.5}$ concentration reductions during the COVID-19 outbreak should be further studied.

Air quality is also improved due to the reduction in emissions from anthropogenic sources (Li et al., 2019; Wang et al., 2017a, 2020a, 2020a; Zhao et al., 2021a; Zhang et al., 2021). Large-scale anthropogenic emission reduction in China provides an excellent opportunity to evaluate the effect on air quality improvement. Large-scale emission reductions for major events include the Summer Olympic Games, Asia-Pacific Economic Cooperation forum, and Grand Military Parade in Beijing. Several studies have explored the effect of emission reduction measures on $PM_{2.5}$ in Beijing during these events (Guo et al., 2016; Han et al., 2016; Wang et al., 2010, 2016, 2017b, 2016; Zhang et al., 2016). The impact scope, impact time, and emission reduction were larger during the COVID-19 outbreak than during the above-mentioned events, owing to the implementation of nationwide contingency plans (Zhao et al., 2020). Understanding the impact of anthropogenic emission reduction on air quality during the COVID-19 outbreak will help guide future control strategies.

Source apportionment of $PM_{2.5}$ during the COVID-19 outbreak was reported for individual cities (Hong et al., 2021; Dai et al., 2020; Cui et al., 2020) and at the regional scale (Li et al., 2020; Ma et al., 2021). Hong et al. (2021) found that the contribution of secondary formation to $PM_{2.5}$ increased during COVID-19; however, other primary sources decreased from pre-lockdown levels in a coastal city of southeast China. $PM_{2.5}$ in the YRD during COVID-19 was produced by industry (32.2%–61.1%), mobility (3.9%–8.1%), dust (2.6%–7.7%), residential sources (2.1%–28.5%), and long-range transport from northern China (14.0%–28.6%) (Li et al., 2020). Implementing unified prevention and control of air pollution is an effective mitigation measure for air quality improvement. Therefore, investigating the source apportionment of $PM_{2.5}$ on a regional scale (e.g., mid-eastern China) plays a critical role in air quality improvement.

We studied six major cities in mid-eastern China (i.e., Beijing, Tianjin, Shijiazhuang, Taiyuan, Jinan, and Zhengzhou) that generated 8.1% of total national gross domestic product (GDP) in 2019 (http://data.stats.gov.cn/index.htm). Although the air quality in the study area has improved, annual $PM_{2.5}$ concentrations in 2020 exceed the annual secondary guideline value (35 μg/m^3; GB3095-2012) by 9%–66% based on the data released by local ecology and environmental bureaus. Investigating the impact of COVID-19 on air quality is important for exploring effective policy making and controlling air pollution measures. Air quality during the COVID-19 outbreak from January 23 to February 29, 2020 was analyzed. The WRF/Chem model was used to evaluate the impacts of meteorology and emission reduction on air quality. Source apportionment of $PM_{2.5}$ during the COVID-19 outbreak was also evaluated.

2. Methods

2.1. Data source

Hourly ambient mass concentrations of $PM_{2.5}$ from 63 monitoring stations in mid-eastern China were downloaded from China's National Environmental Monitoring Centre at https://quotsoft.net/air/. The standard procedure (e.g., monitoring system, analysis method, quality assurance, and quality control) for monitoring of $PM_{2.5}$ are illustrated in the Text S1. Fig. 1 illustrates the locations of the monitoring stations. Additionally, hourly meteorological data (including temperature, relative humidity, and wind speed) were collected from the Meteorological Information Comprehensive Analysis and Process System (MICAPS) of the Chinese Meteorological Administration.

2.2. Modeling system

2.2.1. Model selection and parameter settings

In this study, WRF/Chem was applied to evaluate the impacts of meteorology and emissions during the COVID-19 outbreak on air quality in mid-eastern China. The reliable model is widely used for mesoscale simulations (Chen et al., 2017; Lv et al., 2020; Wang et al., 2020c; Xing et al., 2020). In this study, 30 sigma levels were designed in the vertical dimension. The regional acid deposition model version 2 (RMD2) was chosen as the gas-phase chemistry mechanism. The modal aerosol dynamics model for Europe (MADE/SORGAM) was used to calculate the aerosol chemistry. The initial and lateral meteorological boundary conditions for WRF/Chem were generated from the National Centre for Environmental Prediction (NCEP) Final Analysis (FNL) data, which were available at a $1^\circ \times 1^\circ$ resolution and temporal resolution of 6 h. Our previous work contains more detailed descriptions of WRF/Chem (Chen et al., 2018; Wang et al., 2021; Zhao et al., 2021b). A two-level nested-grid architecture was employed for implementation of the WRF/Chem modeling system (Fig. 1). Domain 1 covers more than half of China, with a grid resolution of 27 km × 27 km. Domain 2 covers mid-eastern China, with a grid resolution of 9 km × 9 km. The simulation periods are from January 23 to February 29, 2020 and from January 23 to February 28, 2019.

2.2.2. Simulation scenarios

Four scenarios were modeled separately to evaluate the impacts of meteorology and emissions on air quality in mid-eastern China. Scenario 1 refers to a baseline scenario with "emissions with the COVID-19 outbreak" with 2020 meteorological conditions (Table 1). Scenario 2 refers to "emissions with the COVID-19 outbreak" with 2019 meteorological conditions. Other configurations (e.g., physical and chemical schemes) for the simulations were the same. Thus, the difference between the modeling results of scenarios 1 and 2 illustrates the impact of meteorology on air quality during the COVID-19 outbreak. Scenario 3 refers to "emissions without the COVID-19 outbreak" with 2020 meteorological conditions. Unconventional and stringent prevention and control measures were implemented in mid-eastern China to prevent further spread of the virus. The difference between the modeling results of scenarios 1 and 3 illustrates the impact of emission reduction during the COVID-19 outbreak on air quality. Scenario 4 was simulated using a zero-out method to quantify sectoral contributions to $PM_{2.5}$ from five source categories (power, industry, residential, transportation, and agriculture emissions) during the COVID-19 outbreak with 2020 meteorological conditions. Differences in modeling results in scenarios 1 and 4 illustrate the contributions of different emission sources on air quality.

2.2.3. Emission inventory

The emission inventory used for the simulation was processed based on the Multi-resolution Emission Inventory for China (MEIC; http://www.meicmodel.org/). The emission inventories available in the MEIC were used to calculate the anthropogenic emission reduction ratios from 2016 to 2017. To calculate the 2019 emission inventory, we assumed that the reduction ratios of anthropogenic emissions from 2018 to 2019 were consistent with those from 2016 to 2017 and that agricultural emissions have not changed in recent years. Zheng et al. (2020a, 2021) reported the reduction ratios of anthropogenic emissions in China from 2019 to 2020 by species, sector, month, and province using a bottom-up approach based on near real-time data. The reduction ratios of total $PM_{2.5}$ decreased by 5%, 1%, and 6% in Beijing, Shandong, and Henan, respectively, in January 2020 compared with the same period in 2019; the $PM_{2.5}$ reduction ratios increased by 4%, 5%, and 4% in Tianjin, Hebei, and Shanxi, respectively, during the same period (Table S1). The reduction ratios of total $PM_{2.5}$ decreased more in February 2020 than in February 2019—by 21%, 24%, 23%, 28%, 24%, and 32% in Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan, respectively—due to the implementation of nationwide contingency plans to shut down traffic and public activities. Therefore, the emissions inventory during the COVID-19 outbreak of 2020 was calculated based on the 2019 emissions inventory and the reduction ratios of anthropogenic emissions from 2019 to 2020—which was the emissions inventory used in scenarios 1, 2, and 4. The emission inventory without the COVID-19 outbreak of 2020 (scenario 3) was also calculated based on the cube of the emission reduction ratios from 2016 to 2017.

Table 1
Description of simulation scenarios.

Type of scenarios	Description	
	Meteorological	Emission
Scenario 1	2020[a]	Emissions with COVID-19 outbreak (the base case)
Scenario 2	2019[b]	Emissions with COVID-19 outbreak
Scenario 3	2020[a]	Emission without COVID-19 outbreak
Scenario 4	2020[a]	No power, industry, residential, transportation, and agriculture emissions, respectively

[a] The simulation periods are from January 23 to February 29, 2020.
[b] The simulation periods are from January 23 to February 28, 2019.

Tables S2 and S3 present the reduction ratios of air pollutants from anthropogenic sources during the 2020 COVID-19 outbreak (scenarios 1, 2, and 4) and without the 2020 COVID-19 outbreak (scenario 3) compared with the same period in 2017. The reduction ratios of air pollutants from anthropogenic emissions in Beijing, Tianjin, Henan, Shanxi, Shandong, and Henan in February 2020 were higher than those in January by 27.5%–72.3%, 34.8%–53.8%, 20.8%–49.4%, and 17.3%–58.1% for power, industry, residential use, and transportation, respectively.

2.2.4. Model evaluation

The performance of the modeling system was evaluated to ensure a reasonable reproduction of the observed air quality levels and meteorological conditions. Statistical indices used for model evaluation include the correlative coefficient (R), the normalized mean bias (NMB), and the normalized mean error (NME), according to the United States Environmental Protection Agency model evaluation protocol (U.S. EPA, 2007). The simulated $PM_{2.5}$ concentration and meteorological parameters (e.g., temperature, relative humidity, and wind speed) from the lowest layer were compared with the observations in six cities from January 23 to February 29, 2020 to evaluate the modeling performance. The simulated $PM_{2.5}$ concentrations were extracted from grids covering 63 monitoring stations in six cities, and the observed concentrations

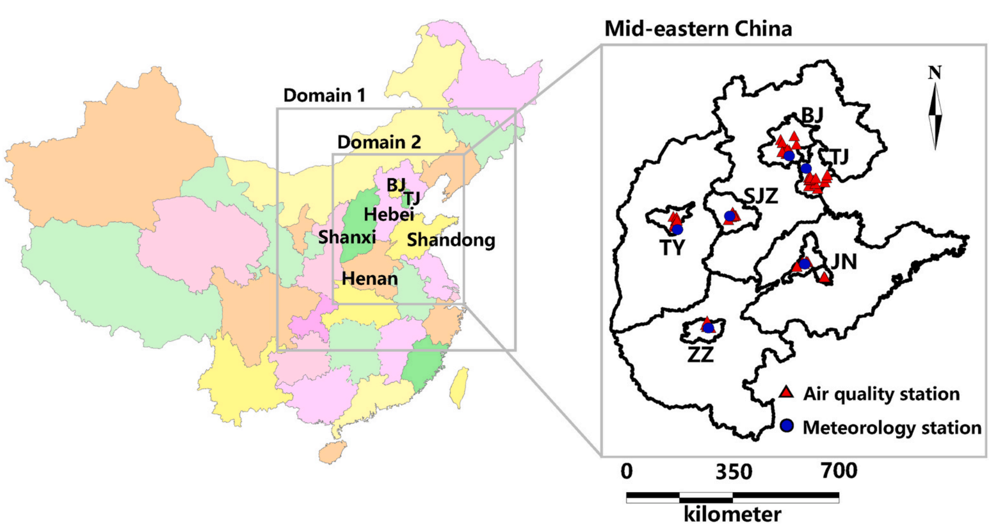

Fig. 1. Modeling domain and locations of monitoring stations in mid-eastern China.

were obtained from China's National Environmental Monitoring Centre. As long as the monitoring stations are covered in the grid cell, the simulated concentration of the grid cell were extracted. The averaged simulated concentration of those grid cells represent the $PM_{2.5}$ simulated concentration of each city. The simulated meteorological parameters were extracted from grids at six monitoring stations (Beijing: 116.47° E, 39.80° N; Tianjin: 117.06° E, 39.43° N; Shijiazhuang: 114.40° E, 38.02° N; Taiyuan: 112.58° E, 37.62° N; Jinan: 117.01° E, 36.60° N; and Zhengzhou: 113.66° E, 34.71° N); the meteorological parameters were obtained from the MICAPS of the China Meteorological Administration (Fig. 1).

The modeling performance of WRF/Chem for simulating air pollutant concentrations and meteorology in mid-eastern China was good during the entire simulation period. The R between the simulated and observed $PM_{2.5}$ data in the six cities were 0.5–0.8, and NME values were 48.4%–68.6% (Table 2). However, the model slightly underestimated the concentrations of $PM_{2.5}$, with an NMB of −68.3%. The agreement of the meteorological parameters between the observed and simulated results in the six cities was also good; the R, NMB, and NME of the temperature ranged from 0.8 to 1.0, 20.2%–66.1%, and 15.9%–127.2%, respectively. The simulated relative humidity was also compared with the observed data; R, NMB, and NME ranged from 0.8 to 0.9, −38.2% to −0.8%, and 12.8%–38.5%, respectively. The R, NMB, and NME of the wind speed ranged from 0.8 to 0.9, 35.1%–62.1%, and 36.1%–62.1%, respectively. Deviations between the simulation and observed values which might be explained by the large uncertainties associated with the estimation of emission reductions during the COVID-19 outbreak and the unavoidable deficiencies of the meteorological and air quality models (Chen et al., 2021).

3. Results and discussion

3.1. Air pollution episodes still occurred during the COVID-19 outbreak

Air pollution episodes occurred during the COVID-19 outbreak (January 23 to February 29, 2020) in mid-eastern China; however, the average $PM_{2.5}$ concentrations in Beijing, Jinan, and Zhengzhou met 2nd-level air quality standards due to reduced emissions (GB3095-2012; Fig. 2). The average daily $PM_{2.5}$ concentration should be less than 75 μg/m^3 for 2nd-level air quality in China. $PM_{2.5}$ concentrations in Tianjin, Shijiazhuang, and Taiyuan were 2.9%–27.8% higher than this standard. Pollution grades are divided into four categories based on daily $PM_{2.5}$ concentrations according to the Technical Regulation on Ambient Air Quality Index (on trial; HJ633-2012). Clean, mildly polluted, moderately polluted, and heavily polluted days correspond to daily $PM_{2.5}$ concentrations of ≤75, 75–115, 115–150, and >150 μg/m^3, respectively. The results indicated that polluted days (the sum of mildly, moderately, and heavily polluted) accounted for 31.5%–60.5% of the total number of outbreak days in mid-eastern China during the study period (Fig. 2). In particular, 10.5%–23.7% of the days during the COVID-19 outbreak were heavily polluted in Beijing, Tianjin, Shijiazhuang, and Taiyuan; thus, the government faces a considerable challenge to effectively tackle current air pollution in mid-eastern China, despite extreme reductions in primary emissions. Therefore, enhanced regional environmental cooperation should be considered.

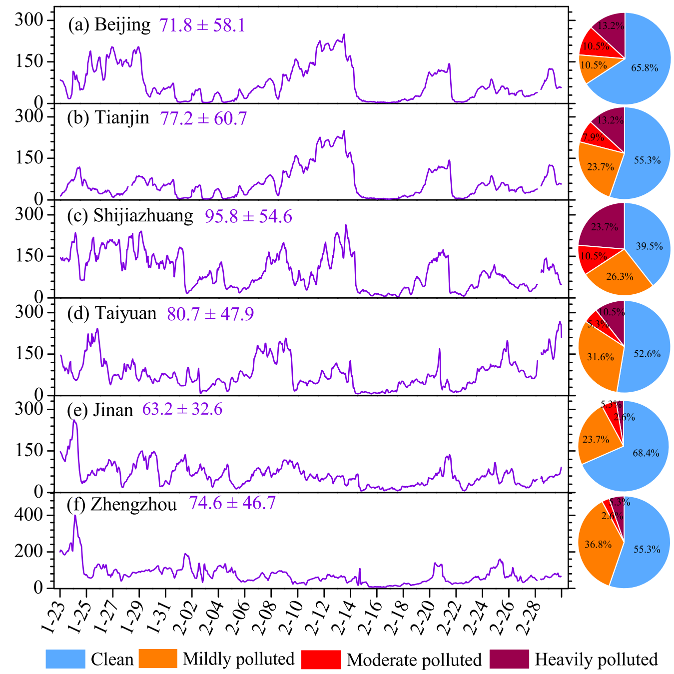

Fig. 2. Time series of $PM_{2.5}$ concentrations and proportion of different pollution grades during the COVID-19 outbreak of 2020 in mid-eastern China.

3.2. Improved air quality with 2019 COVID-19 outbreak, except Jinan in and Zhengzhou

$PM_{2.5}$ concentrations would have decreased in mid-eastern China—except in Jinan and Zhengzhou—had the COVID-19 outbreak occurred in 2019 instead of 2020. The impact of meteorological changes on air quality in mid-eastern China during the COVID-19 outbreak was analyzed using the WRF/Chem model. The temporal and spatial distributions of pollutant concentrations under two different meteorological conditions with the same emission inventory (scenarios 1 and 2, Table 1) were simulated. Fig. 3 shows the spatial distribution of the $PM_{2.5}$ concentration reduction ratios caused by meteorological changes from 2019 to 2020. The meteorological conditions during the COVID-19 outbreak of 2019 were more favorable for reducing $PM_{2.5}$ than those during the same period in 2020 and led to reductions of 29.2%, 16.5%, 4.0%, and 9.2% in Beijing, Tianjin, Shijiazhuang, and Taiyuan, respectively. Unfavorable meteorological conditions led to $PM_{2.5}$ increases in Jinan and Zhengzhou of 11.5% and 6.1%, respectively.

The relatively good air quality during COVID-19 in 2019 was dominated by favorable meteorological conditions featuring high wind speeds and low relative humidity. We compared the hourly meteorological data of the six cities during the COVID-19 period of 2020 to the

Table 2
Comparison of $PM_{2.5}$ concentrations and meteorological parameters between observed and simulated data during the COVID-19 outbreak from January 23 to February 29, 2020 in mid-eastern China.

Region	$PM_{2.5}$ (μg/m^3)			Temperature (°C)			Relative humidity (%)			Wind speed (m/s)		
	R	NMB (%)	NME (%)	R	NMB (%)	NME (%)	R	NMB (%)	NME (%)	R	NMB (%)	NME (%)
Beijing	0.8	−30.3	48.4	0.9	66.1	70.2	0.8	−38.2	38.5	0.9	38.5	38.7
Tianjin	0.8	−51.7	61.8	0.8	26.2	127.2	0.8	−28.8	32.1	0.9	62.1	62.1
Shijiazhuang	0.8	−68.2	68.6	0.9	20.4	31.8	0.9	−30.5	31.9	0.8	35.1	36.1
Taiyuan	0.5	−50.2	62.7	0.9	58.0	65.9	0.8	−7.4	16.5	0.9	36.7	38.3
Jinan	0.5	−60.4	64.3	1.0	−20.2	27.5	0.8	−0.8	14.1	0.8	54.9	54.9
Zhengzhou	0.8	−54.1	60.9	0.9	0.0	15.9	0.9	−8.6	12.8	0.9	55.4	55.4

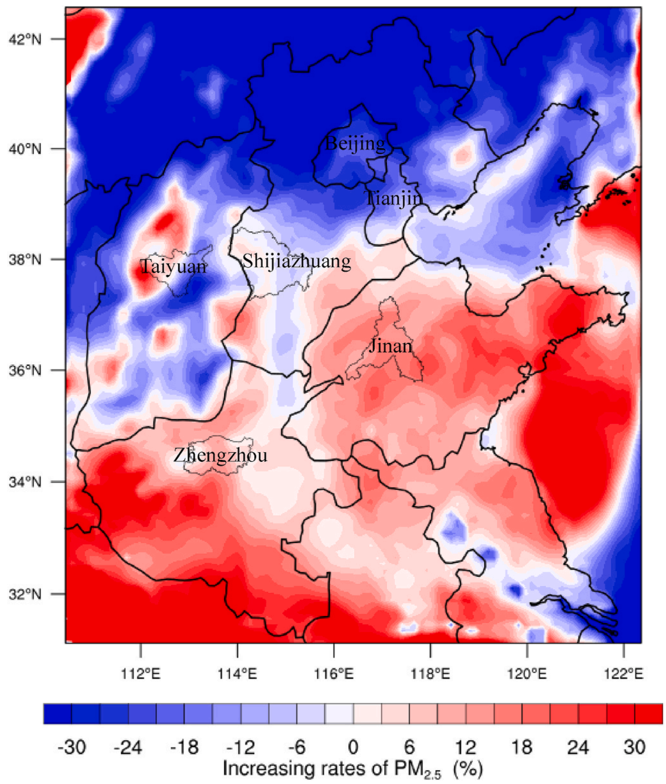

Fig. 3. Spatial distribution of reduction ratios of $PM_{2.5}$ concentrations caused by meteorological changes from 2019 to 2020.

same period in 2019 (Fig. 4). The wind speeds during COVID-19 in 2019 changed by 23.9%, 45.8%, −1.2%, 20.1%, 5.0%, and −10.1% in Beijing, Tianjin, Shijiazhuang, Taiyuan, Jinan, and Zhengzhou, respectively, compared with the same period in 2020. The humidity in the aforementioned cities decreased by 41.2%, 38.2%, 20.6%, 26.4%, 15.2%, and 9.0%, respectively. An unstable vertical atmospheric structure strengthens the atmospheric turbulent exchange and diffusion of air pollutants in the vertical direction (Shen et al., 2018; Zhang et al., 2013). High humidity during the 2020 COVID-19 period promoted the conversion of precursor gases (e.g., SO_2, NO_x, and NH_3) to $PM_{2.5}$. Zheng et al. (2020b) reported that levels of sulfate, organic carbon, and secondary inorganic aerosols increased by 2.5%–8.7% in Wuhan city from January 23 to February 22, 2020, suggesting the enhanced secondary formation of $PM_{2.5}$ with increased humidity. Our previous results found that the increasing conversions from precursor gases to corresponding particulate phases resulted in higher $PM_{2.5}$ concentrations during heavy pollution episodes (Liu et al., 2017; Wang et al., 2021). Therefore, in terms of wind speed and humidity, the meteorological conditions during COVID-19 in 2019 were more favorable for the diffusion of pollutants compared with the same period in 2020.

The reductions in $PM_{2.5}$ concentrations in scenarios 1 and 2 and the observed $PM_{2.5}$ concentrations from January 23 to February 29, 2020 were used to calculate $PM_{2.5}$ concentrations in scenario 2. Polluted days accounted for 24.8%–56.8% of the total number of outbreak days in mid-eastern China during the study period (Fig. S1) and were reduced by 9.9%, 12.3%, 3.8%, 9.5%, and 6.9% in Beijing, Tianjin, Shijiazhuang, Taiyuan, and Zhengzhou, respectively, compared with scenario 1. The frequency of polluted days increased by 19.8% in Jinan, primarily due to the increase in mildly polluted days from 9 to 14. The frequency of heavily polluted days decreased by 10.5%, 10.5%, and 12.9% in Beijing, Tianjin, and Shijiazhuang, respectively; changed little in Taiyuan and Jinan; and increased by 11.0% in Zhengzhou.

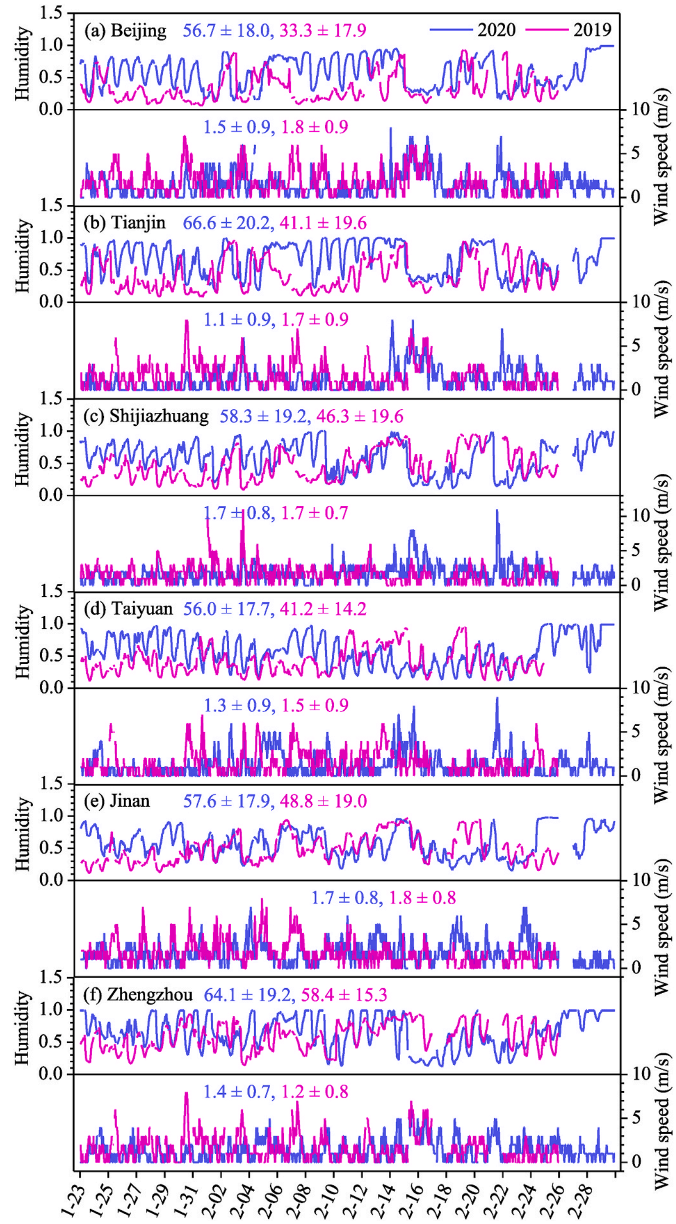

Fig. 4. Time series of meteorological parameters during the COVID-19 outbreak in mid-eastern China.

3.3. *$PM_{2.5}$ concentration increased by 10.9%–20.5% without the COVID-19 outbreak*

Emissions changed greatly during the COVID-19 outbreak and would otherwise have increased the degree of air pollution due to human activities. We investigated hypothetical air quality in mid-eastern China with and without the COVID-19 outbreak and simulated the spatio-temporal distribution of pollutant concentrations (scenarios 1 and 3, Table 1) to evaluate the impact of emission changes.

Fig. 5 shows the spatial distribution of increasing $PM_{2.5}$ concentrations caused by emission changes due to the COVID-19 outbreak. Air quality deteriorated without the COVID-19 outbreak; and $PM_{2.5}$ concentrations increased by 14.5%, 12.5%, 10.9%, 18.6%, 14.6%, and 20.5%, in Beijing, Tianjin, Shijiazhuang, Taiyuan, Jinan, and Zhengzhou, respectively (Fig. 5). Thus, Zhengzhou and Taiyuan had more pronounced air quality improvement than other cities during the COVID-19 outbreak. Therefore, the lockdown implementation response of each city was different. The total $PM_{2.5}$ concentration subjected to

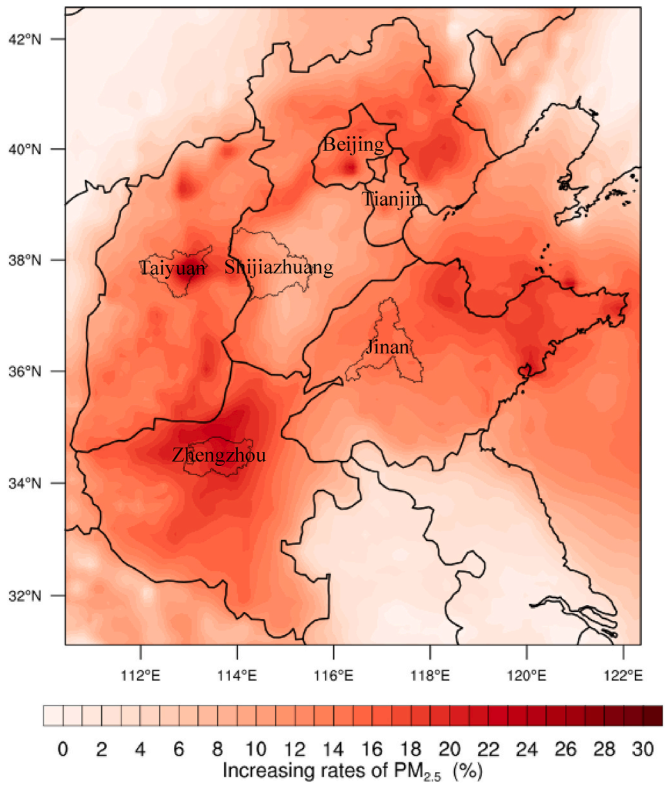

Fig. 5. Spatial distribution of increasing rates of $PM_{2.5}$ concentrations caused by emissions changes due to the COVID-19 outbreak.

emission reduction (scenario 1) decreased by more than 20% over the entire YRD compared to scenario 3 levels (without emission reduction) (Ma et al., 2021). The results from Ma et al. (2021) were higher than those in this study (10.0%–20.5%), primarily because the reductions of $PM_{2.5}$ from anthropogenic emissions during the COVID-19 outbreak in the studied regions (Beijing, Tianjin, Hebei, Shanxi, Shandong, and Henan) ranged from 1% to 6% in January and 21%–32% in February and were lower than those in the YRD region (4%–15% in January and 25%–42% in February for Shanghai, Jiangsu, Zhejiang, and Anhui) (Zheng et al., 2020a, 2021, 2021).

The reductions in $PM_{2.5}$ concentrations between scenarios 1 and 3 and the observed $PM_{2.5}$ concentrations from January 23 to February 29, 2020 were used to calculate $PM_{2.5}$ concentrations in scenario 3. Polluted days accounted for 39.1%–71.1% of the total number of outbreak days in mid-eastern China during the study period (Fig. S2); the frequencies increased by 5.3%, 5.3%, 10.5%, 13.2%, 7.9%, and 18.4% in Beijing, Tianjin, Shijiazhuang, Taiyuan, Jinan, and Zhengzhou, respectively, compared with those in scenario 1. The number of heavily polluted days increased by 5.3% and 7.9% in Tianjin and Taiyuan, respectively.

3.4. Industry and residential use were the dominant $PM_{2.5}$ contributors during the COVID-19 outbreak

The source contributions to $PM_{2.5}$ concentrations for Beijing, Tianjin, Shijiazhuang, Taiyuan, Jinan, and Zhengzhou during the COVID-19 outbreak were quantified using the WRF/Chem model and divided into power, industry, residential, transportation, and agriculture. The contributions of each emission source to average $PM_{2.5}$ concentrations were calculated by the concentration difference between scenarios 1 and 4 (Table 1).

Industry and residential emissions were the dominant $PM_{2.5}$ contributors in the six cities in mid-eastern China during the COVID-19 outbreak, with contributions of 32.7%–49.6% and 26.0%–44.5%, respectively, followed by agriculture (18.7%–24.0%), transportation (7.7%–15.5%), and power (4.1%–5.9%) (Fig. 6); this is consistent with the results in the YRD region (Li et al., 2020). Although medium, small, and service industry emissions decreased due to the COVID-19 outbreak, the emission reduction of large-scale enterprises (e.g., iron and steel, petrochemical) that maintain the needs of human society is limited. Industrial emissions increased by 5%–18% in January 2020 compared with the same period of 2019 in the study area, except in Beijing (Table S1). The residential emission reduction rate was relatively lower than that of other sources. Emissions decreased by 8%–17% in February 2020 and did not change in January 2020 compared to the same period in 2019 (Table S1), primarily due to the lockdown that shut down public activities to prevent further spread of the virus. The study period covered the Spring Festival holidays from January 24 to February 2, 2020. In contrast to the holiday in previous years, migrant workers could not return to their hometowns to visit relatives and friends. Thus, almost everyone was isolated at home during the COVID-19 pandemic, increasing the contribution of residential sources to $PM_{2.5}$. Ma et al. (2021) reported that contributions from the residential sector increased by more than 10%–35% during COVID-19 compared with contributions without emission reductions over the YRD region. Therefore, developing an advanced industrial emission reduction technology and installing efficient cooking fume purification systems is urgently necessary to improve air quality.

Contributions of industry and residential use to $PM_{2.5}$ concentrations in Beijing were lower (32.7%) and higher (44.5%), respectively, in Beijing than in other cities (38.7%–49.6% for industry and 26.0%–36.2% for residential; Fig. 6). This was primarily due to $PM_{2.5}$ and emissions from industry in Tianjin, Hebei, Shanxi, Shandong, and Henan, which were 1.9–18.4 higher than those in Beijing (http://www.meicmodel.org/). In addition, a large reduction in industrial emissions was found in Beijing during the COVID-19 outbreak compared to the same period in 2019 (Table S1). In January 2020, $PM_{2.5}$ emissions decreased by 19%, while emissions in other regions increased (5%–18%). In February 2020, the reduction in $PM_{2.5}$ emissions in Beijing (45%) was higher than that in other regions (34%–42%). The permanent population in Beijing in 2019 was 21.5 million (Beijing Municipal Bureau Statistics; http://tjj.beijing.gov.cn/)—1.4–4.8 times that in other cities (4.5–15.6 million). Most migrant workers and students were isolated in Beijing because of restricted construction and traveling.

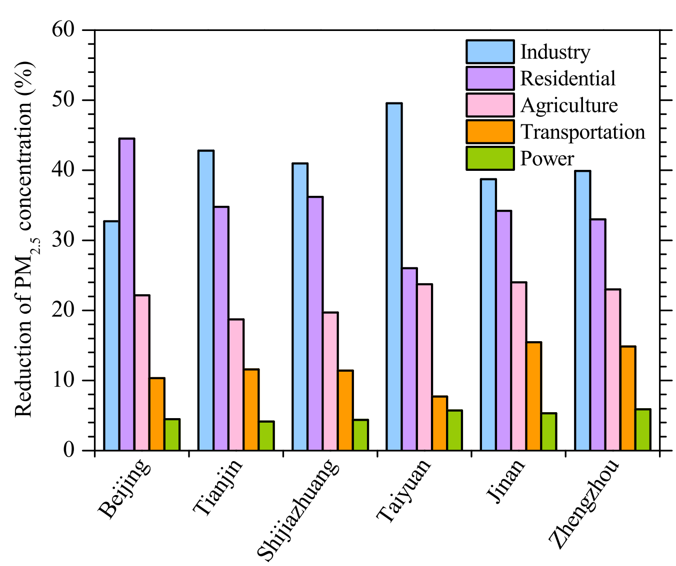

Fig. 6. Contribution of emission sources to $PM_{2.5}$ concentrations during the COVID-19 outbreak of 2020.

4. Conclusion

Investigating the impacts of meteorology and emission reduction on air quality during the COVID-19 outbreak will help guide future control strategies. Polluted days (the sum of mildly, moderately, and heavily polluted days) accounted for 31.5%–60.5% of the total number of outbreak days in mid-eastern China from January 23 to February 29, 2020, indicating that anthropogenic emission reduction cannot completely offset the impact of unfavorable meteorological conditions on air quality. The WRF/Chem model Air results shows that quality would have improved if the COVID-19 outbreak had occurred in 2019 instead of 2020 (except in Jinan and Zhengzhou). Meteorological conditions favoring decreased $PM_{2.5}$ concentrations were characterized by high wind speeds and decreased relative humidity in 2019. Therefore, meteorological conditions should be considered when designing control strategies. The air quality deteriorated without the COVID-19 outbreak of 2020, with $PM_{2.5}$ concentrations increasing by 10.9%–20.5% and polluted days increased by 5.3%–18.4% in mid-eastern China. Industry and residential emissions were the dominant contributors in the six cities (contributions of 32.6%–49.6% and 26.6%–44.5%, respectively), followed by agriculture, transportation, and power. In addition, the contributions of industry and residential use to $PM_{2.5}$ concentrations were lower and higher in Beijing than in other cities. Therefore, the development of industrial control technology and efficient cooking fume purification systems should be developed to improve air quality.

Author statement

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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.2021.118750.

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