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Impacts of the meteorological condition versus emissions reduction on the PM$_{2.5}$ concentration over Beijing–Tianjin–Hebei during the COVID-19 lockdown

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A R T I C L E   I N F O

Keywords:
PM$_{2.5}$
WRF-Chem
Meteorological condition
Emissions reduction

A B S T R A C T

The impacts of the meteorological condition and emissions reduction on the aerosol concentration over the Beijing–Tianjin–Hebei (BTH) region during the COVID-19 lockdown were analyzed by conducting three numerical experiments, including one with the meteorological field in 2019 and MEIC-2019 (2019 monthly Multi-resolution Emissions Inventory for China), one with the meteorological field in 2020 and MEIC-2019, and one with the meteorological field in 2020 and MEIC-2020, via a WRF-Chem model. The numerical experiments were performed from 3 to 16 February in 2019 and in 2020, during which a severe fog–haze event (3–16 February 2020) occurred in the BTH region, with a simulated maximum daily PM$_{2.5}$ of 245 µg m$^{-3}$ in Tangshan and 175 µg m$^{-3}$ in Beijing. The results indicate that the daily PM$_{2.5}$ decreased by 5–150 µg m$^{-3}$ due to the emissions reduction and increased by 10–175 µg m$^{-3}$ due to the meteorological condition in Beijing, Shijiazhuang, Tangzhou, Handan, Benghui, Chengde, Zhangjiakou, and Tangshan from 7 to 14 February. For the horizontal distribution, PM$_{2.5}$ and different aerosol species concentrations from 7 to 14 February 2020 increased compared with those during the same period in 2019, indicating that the accumulation of pollutants caused by the unfavorable meteorological condition offset the decreases caused by the emissions reduction, leading to the high aerosol concentration during the COVID-19 lockdown.

ABSTRACT

The impacts of the meteorological condition and emissions reduction on the aerosol concentration over the Beijing–Tianjin–Hebei (BTH) region during the COVID-19 lockdown were analyzed by conducting three numerical experiments, including one with the meteorological field in 2019 and MEIC-2019 (2019 monthly Multi-resolution Emissions Inventory for China), one with the meteorological field in 2020 and MEIC-2019, and one with the meteorological field in 2020 and MEIC-2020, via a WRF-Chem model. The numerical experiments were performed from 3 to 16 February in 2019 and in 2020, during which a severe fog–haze event (3–16 February 2020) occurred in the BTH region, with a simulated maximum daily PM$_{2.5}$ of 245 µg m$^{-3}$ in Tangshan and 175 µg m$^{-3}$ in Beijing. The results indicate that the daily PM$_{2.5}$ decreased by 5–150 µg m$^{-3}$ due to the emissions reduction and increased by 10–175 µg m$^{-3}$ due to the meteorological condition in Beijing, Shijiazhuang, Tangzhou, Handan, Benghui, Chengde, Zhangjiakou, and Tangshan from 7 to 14 February. For the horizontal distribution, PM$_{2.5}$ and different aerosol species concentrations from 7 to 14 February 2020 increased compared with those during the same period in 2019, indicating that the accumulation of pollutants caused by the unfavorable meteorological condition offset the decreases caused by the emissions reduction, leading to the high aerosol concentration during the COVID-19 lockdown.

1. Introduction

There was a case of pneumonia caused by coronavirus in Wuhan city, Hubei Province, China, at the end of December 2019. Subsequently, the coronavirus was officially named Coronavirus Disease 2019 (COVID-19) by the World Health Organization (WHO 2020), and it quickly spread to Hubei Province and other parts of the country. During the Chinese New Year holiday, the government formulated policies to reduce the spread of the virus by reducing contact and increasing physical distance. As a part of these social policies, the Chinese government encouraged people to stay at home rather than attending mass gatherings, canceled or post-poned large-scale public events, and delayed the opening of universities

and the resumption of factory work. Only a limited part of the urban public transportation system was in operation, and all interprovincial bus routes were suspended (Tian et al., 2020; Chen et al., 2020). These measures reduced the number of vehicles on the road, as well as industrial operations and restaurants in operation, which are the emission sources of air pollution, especially in winter. Human and industrial activities were reduced to basic or minimal levels (Zhang et al., 2019). Compared with that at the beginning of January 2020, the NO$_2$ concentration in China dropped sharply in mid-February 2020, according to NASA satellite data (NASA, 2020). The data provided by the pollution monitoring agency showed that the PM$_{2.5}$ decreased by an average of 15–17 µg m$^{-3}$ d$^{-1}$ in February 2020 compared with that in January 2020. The quantity of carbon dioxide emissions, e.g., emissions from coal and crude oil, decreased by 25% during the COVID-19 lockdown compared to the same period in 2019 in the North China Plain region.

https://doi.org/10.1016/j.aosl.2020.100014

Received 11 August 2020; Revised 17 September 2020; Accepted 9 October 2020

Available online 10 December 2020

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(Kerimray et al., 2020). The effect of these measures on reducing pollutant concentrations during the COVID-19 lockdown has been widely discussed (Wang et al., 2020; Collivignarelli et al., 2020; Li et al., 2020).

Despite the significant reduction in emissions, several serious fog-haze events occurred in the North China Plain region during the COVID-19 lockdown, arousing great concern. Specifically, the PM$_{2.5}$ reached 181–208 µg m$^{-3}$ in Beijing on 10–13 February (Nichol et al., 2020) and increased by approximately 30%–50% compared to that during the period before the COVID-19 lockdown over the Beijing–Tianjin–Hebei (BTH) region (Huang et al., 2020). Therefore, to evaluate the impact of the meteorological condition and emissions reduction on the near-surface PM$_{2.5}$ during the COVID-19 lockdown, three numerical experiments with different meteorological fields and emission sources were conducted by using a coupled meteorology and aerosol/chemistry model (WRF-Chem).

2. Data and model description

The online coupled model WRF-Chem simultaneously simulates the meteorological field and the concentrations of gases and aerosols (Grell et al., 2005). In this study, WRF-Chem (v4.1.2) was configured to cover the east part of China with 100 (south–north) × 90 (west–east) grid points and a 27-km horizontal resolution centered on central China (38.0°N, 116.5°E). The vertical direction was divided into 36 layers, and the average height of the first layer was approximately 30 m. The model domain is shown in Fig. S1 in the supplementary file. The meteorological initial and lateral boundary conditions used in WRF-Chem were from the NCEP FNL (final) analysis data with a 1° × 1° spatial resolution. Four-dimensional data assimilation (Werner et al., 2018) was used to improve the accuracy of the simulation results. The nudging coefficients of temperature, water vapor, and horizontal wind components were $3 \times 10^{-4}$ s$^{-1}$, $1 \times 10^{-5}$ s$^{-1}$, and $3 \times 10^{-4}$ s$^{-1}$, respectively (Otto, 2008). The chemical initial and boundary conditions were from the global chemical forecast output of the Whole Atmosphere Community Climate Model (Marsh et al., 2013). Details regarding the parameterization schemes used in this study are listed in Table S1.

Anthropogenic emissions of carbon monoxide, nitrogen oxide, sulfur dioxide, volatile organic compounds, black carbon (BC), organic carbon (OC), PM$_{2.5}$, and PM$_{10}$ were based on the 2016 monthly Multi-resolution Emission Inventory for China (MEIC-2016) (http://www.meicmodel.org). Then, MEIC-2016 was projected to the year 2019 (MEIC-2019) according to the anthropogenic emission trends provided by Tong et al. (2020) to make the emissions more reasonable. Since there is no anthropogenic emissions information for the year 2020, the emissions for 2020 (MEIC-2020) were calculated according to the suggestion from the Chinese Research Academy of Environmental Sciences (http://www.craes.cn/zjhky/zsjg/kydw/gjdw/gjdwrfz/), as follows: transportation, industry and power emissions decreased by 80%, 40%, and 50%, respectively; residential emissions increased by 30%; and agricultural emissions remained unchanged. Biogenic emissions were calculated online through a natural gas and aerosol emission model, MEGAN (Model of Emissions of gases and Aerosols from Nature), version 2.01 (Guenther et al., 2006). The biomass burning emissions were based on the Fire Inventory from NCAR (Wiedinmyer et al., 2014). Dust emissions were calculated online according to the method of Shao et al. (2011). Sea salt emissions were calculated online with reference to Gong et al. (1997).

To investigate the causes of the high near-surface PM$_{2.5}$ concentration in the BTH region during the COVID-19 lockdown, three experiments were conducted from 20 January to 16 February, including the time for model spin-up, with the model evaluation and results analysis conducted from 3 to 16 February. The first experiment was conducted with the meteorological field in 2019 and MEIC-2019 (19M19E). The second experiment was conducted with the meteorological field in 2020 and MEIC-2019 (20M19E). And the third sensitivity experiment was conducted with the meteorological field in 2020 and MEIC-2020 (20M20E). The biogenic emissions, biomass burning, chemical initial and boundary conditions, and physical and chemical parameterization schemes were the same for all experiments. The effect of the meteorological condition on the near-surface PM$_{2.5}$ concentration could be estimated as the difference between 20M19E and 19M19E. The effect of emissions reduction on the near-surface PM$_{2.5}$ concentration could be estimated as the difference between 20M20E and 20M19E.

The near-surface meteorological field and pollutant concentration data used for model evaluation were derived from the open dataset of the Meteorological Science and Technology Application Center (http://159.226.234.52/), of which the meteorological field data were derived from the National Meteorological Information Center (http://data.cma.cn/data/detail/dataCode/A.0012.0001.html) and the pollutant concentration data from the Air Quality Historical Data Platform (https://aqicn.org/data-platform/register/cn/). The observation and the corresponding model results were all averaged over several observation stations in each city, including BJ (Beijing), TJ (Tianjin), SJZ (Shijiazhuang), ZJK (Zhangjiakou), CZ (Cangzhou), HD (Handan), HS (Hengshui), CD (Chengde), TS (Tangshan), and QHD (Qinhuangdao). Detailed information for the stations in each city is provided in the supplementary file.

The model performance for the meteorological parameters and pollutant concentrations are shown in the supplementary file (Figs. S1–S4 and Tables S1–S2). The results show that the WRF-Chem model performs well in the simulation of the meteorological condition and pollutant concentrations. This good performance of the model gives us the confidence to apply it to study the impacts of the meteorological condition and emissions reduction on the PM$_{2.5}$ concentration.

3. Impacts of the meteorological condition and emissions reduction on the near-surface PM$_{2.5}$ concentration

The impacts of the meteorological condition and emissions reduction on the near-surface PM$_{2.5}$ concentration during the COVID-19 lockdown are discussed in this section. Fig. 1 shows the time series of the modeled daily near-surface PM$_{2.5}$ concentration during 3–16 February 2019 (19M19E) and 3–16 February 2020 (20M20E), the differences between the observed PM$_{2.5}$ in 2019 and 2019 (OBS_change), and the modeled PM$_{2.5}$ between 20M20E and 19M19E (ALL), between 20M19E and 19M19E (MET), and between 20M20E and 20M19E (EMI), which was averaged at the sites in BJ, SJZ, CZ, HD, HS, CD, ZJK, and TS. It can be seen that the daily PM$_{2.5}$ was higher than 100 µg m$^{-3}$ at BJ, SJZ, CZ, HD, HS, and TS, and was $50 \mu g m^{-3}$ at CD and ZJK, during 3–16 February 2019. However, during the same period in 2020, a serious pollution incident occurred in the BTH region. The highest daily PM$_{2.5}$ was 245 µg m$^{-3}$ at TS on 10 February, 175 µg m$^{-3}$ at BJ on 14 February, and exceeded 75 µg m$^{-3}$ at SJZ, CZ, HD, and ZJK on 7–14 February. The daily PM$_{2.5}$ over the BTH region in 2020 was lower than that in 2019 during 3–6 February. However, the daily PM$_{2.5}$ in 2020 was higher than that in 2019 in most cities of the BTH region, with an average increase of approximately 50 µg m$^{-3}$ at BJ, CZ, HD, HS, CD, ZJK, and TS on 7–14 February, and an average increase of approximately 30 µg m$^{-3}$ at SJZ on 7–8 February.

Fig. 1 also shows that the changes in the simulated daily PM$_{2.5}$ between 2020 and 2019 (ALL) agree well with the observed changes (OBS_change), indicating that the model can reproduce the daily PM$_{2.5}$ change between 2020 and 2019. The meteorological condition and emissions reduction have different impacts on PM$_{2.5}$ in different cities. As seen in Fig. 1, emissions reduction led to a decrease of $\sim150$ µg m$^{-3}$ in the daily PM$_{2.5}$ at BJ, SJZ, CZ, HD, HS, CD, ZJK, and TS. For example, PM$_{2.5}$ decreased by up to 100 µg m$^{-3}$ at BJ and by 120 µg m$^{-3}$ at TS on 10 February. In contrast to the emissions reduction, the meteorological condition led to an increase in the daily PM$_{2.5}$, with values of 10–175 µg m$^{-3}$ at BJ, CZ, HD, HS, CD, ZJK, and TS from 7 to 14 February, and 50–100 µg m$^{-3}$ at SJZ on 7–8 February and 13 February. On 3–5 and 15–16 February, the daily PM$_{2.5}$ decreased due to the me-
The impact of the meteorological condition on PM$_{2.5}$ (MET) has a trend that is similar to the combined effects of the meteorological condition and emissions reduction on PM$_{2.5}$ (ALL). This indicates that the meteorological condition tends to determine the temporal variation in the daily PM$_{2.5}$, while the emissions reduction tends to decrease the average value of the daily PM$_{2.5}$. In particular, in BJ on 13 February 2020, when the increase in the daily PM$_{2.5}$ was the highest (approximately 75 μg m$^{-3}$) relative to the same period in 2019, the emissions reduction decreased the daily PM$_{2.5}$ by approximately 100 μg m$^{-3}$ and the meteorological condition increased it by approximately 175 μg m$^{-3}$. There were similar results in other cities. Fig. S5 shows the difference in the observed PM$_{2.5}$ concentration between 2020 and 2019 (OBS_change) and the difference in the modeled PM$_{2.5}$ concentration between 20M20E and 19M19E (ALL), between 20M19E and 19M19E (MET), and between 20M20E and 20M19E (EMI), in which the concentrations are averaged for the period 7–14 February and at the sites in BJ, SJZ, CZ, HD, HS, CD, ZJK, and TS. It can be seen that, during the period 7–14 February, both the observed and simulated PM$_{2.5}$ changes between 2020 and 2019 were synchronized between the different cities, such as BJ, CZ, HD, HS, CD, and ZJK. The meteorological condition–induced PM$_{2.5}$ change was always positive, except at SJZ. The average increases in PM$_{2.5}$ due to the meteorological condition were 13–93 μg m$^{-3}$ at...
BJ, SJZ, CZ, HD, CD, ZJK and TS. In contrast, the emissions reduction in all the cities was negatively correlated with PM$_{2.5}$, with an average decrease of 16–65 $\mu$g m$^{-3}$. The increase in PM$_{2.5}$ caused by the meteorological condition at BJ, CZ, HD, HS, CD, ZJK, and TS was greater than that caused by the emissions reduction.

Fig. 2 shows the horizontal distribution of the differences in the modeled PM$_{2.5}$, SO$_4^{2-}$, NO$_3^-$, NH$_4^+$, BC, and OC concentrations between 20M20E and 19M19E (ALL), 20M19E and 19M19E (MET), and 20M20E and 20M19E (EMI), and the difference in the observed near-surface PM$_{2.5}$ between 2019 and 2020, which were averaged for 7–14 February, the severe pollution period over the BTH region. It can be seen that the changes in the simulated daily PM$_{2.5}$ between 2020 and 2019 agree well with the observed changes, indicating that the model can reproduce the horizontal distribution of the PM$_{2.5}$ change between 2020 and 2019. In the BTH region, compared to 2019, the increase in PM$_{2.5}$ in 2020 mainly occurred in Beijing, Langfang and Tianjin, with values of 50–70 $\mu$g m$^{-3}$. The PM$_{2.5}$ increased by 10–30 $\mu$g m$^{-3}$ in other areas of the BTH region, but not in western Hebei Province. The second
column panels of Fig. 2 shows that the meteorological condition led to an increase in PM$_{2.5}$, with a value higher than 110 $\mu$g m$^{-3}$ in Beijing, Langfang, and Tianjin, and 10–50 $\mu$g m$^{-3}$ in most other areas of Hebei Province. Such an increase in southern Hebei Province was greater than that in northern Hebei Province. In contrast, the third column panels of Fig. 2 shows that the emissions reduction led to a decrease in PM$_{2.5}$, with values of 50–70 $\mu$g m$^{-3}$ in Beijing, Langfang, and Tianjin, approximately 10 $\mu$g m$^{-3}$ in northern Hebei Province and Beijing, and 30 $\mu$g m$^{-3}$ in southern Hebei Province.

For SO$_4^{2-}$, its concentration only slightly increased (by 1–2 $\mu$g m$^{-3}$) in Beijing, Langfang, and Tianjin in 2020 relative to that in 2019. The meteorological condition–induced SO$_4^{2-}$ concentration increased by 1–2 $\mu$g m$^{-3}$ and the emissions reduction–induced SO$_4^{2-}$ decreased by 0.4–1.5 $\mu$g m$^{-3}$ in the BTH region. The distributions of the NO$_3^-$ and NH$_4^+$ concentration changes are similar, with a decrease of 5–10 $\mu$g m$^{-3}$ and 2–4 $\mu$g m$^{-3}$ in the north of the BTH region and an increase of 5–20 $\mu$g m$^{-3}$ and 2–4 $\mu$g m$^{-3}$ in the south of the BTH region in 2020 relative to those in 2019, respectively. Due to the meteorological condition, the increases in the NO$_3^-$ and NH$_4^+$ concentrations were 10–50 $\mu$g m$^{-3}$ and more than 2–14 $\mu$g m$^{-3}$. Due to the emissions reduction, the NO$_3^-$ and NH$_4^+$ concentrations decreased by 20–40 $\mu$g m$^{-3}$ and 7–12 $\mu$g m$^{-3}$. The decrease in the NO$_3^-$ and NH$_4^+$ concentrations caused by the emissions reduction was the highest among the different aerosol species. The BC and OC concentrations increased in most areas of the BTH region in 2020 relative to those in 2019. The BC concentration increased by more than 12 $\mu$g m$^{-3}$ in central Hebei Province and Tianjin and 2–7 $\mu$g m$^{-3}$ in other areas of Hebei Province and northern Beijing, and slightly decreased (by 2–4 $\mu$g m$^{-3}$) in western Beijing. The OC concentration increased by 20–30 $\mu$g m$^{-3}$ in central Hebei Province and 5–20 $\mu$g m$^{-3}$ in other areas. The meteorological condition–induced BC and OC concentrations increased by 1–12 $\mu$g m$^{-3}$ and 1–25 $\mu$g m$^{-3}$, respectively. The emissions reduction–induced BC concentration decreased slightly, with values of 1–4 $\mu$g m$^{-3}$ in a small part of Beijing, Tianjin, and eastern Hebei Province, while the OC concentration increased by approximately 5 $\mu$g m$^{-3}$ in the BTH region due to the increase in residential emissions.

Fig. 3 shows the horizontal distribution of the change in the meteorological parameters in 2020 relative to those in 2019 for the period 7–14 February over the BTH region. It can be seen that the temperature at 2 m above ground (T) and the relative humidity (RH) increased in most areas of the BTH region, with average values of approximately 10°C and 20%, respectively, during the COVID-19 lockdown. The wind speed (WS) decreased by approximately 1 m s$^{-1}$ in Zhangjiakou and Chengde and slightly decreased (0.2 m s$^{-1}$) in other areas of the BTH region. The planetary boundary layer height (PBLH) decreased by approximately 200 m in the north of Beijing, Zhangjiakou and Chengde, and by 50–200 m in other areas of the BTH region. Table S4 shows the linear fitting coefficients between T, RH, WS, PBLH changes and PM$_{2.5}$ changes of 19M19E and 20M19E. It can be seen that the fitting coefficients of T and RH changes are positive, indicating that the PM$_{2.5}$ in different cities increases with the increase in temperature, but the
proportions are different. A higher temperature and relative humidity usually accelerate the formation of secondary aerosols by accelerating chemical reactions (Li et al., 2018; Wang et al., 2019). The fitting coefficient of WS and PBLH is negative, indicating that the lower WS in the BTH region inhibits the diffusion of air pollutants and the lower PBLH enhances atmospheric stability (Liu et al., 2017). For BJ, CD and TS, the absolute value of the fitting coefficient of WS is maximum, indicating that WS changes are the dominant contributor for PM$_{2.5}$ changes. RH is the dominant contributor of PM$_{2.5}$ change in SJZ, CZ, and HS, and T is the dominant contributor in HD and ZJK.

As we know, atmospheric stability has a great influence on PM$_{2.5}$ (Han et al. 2014). The profile of the temperature can be used to characterize the stability of the atmosphere. Fig. S6 shows the temperature (°C) profiles for 19M19E and 20M19E at 0200 LST, 0800 LST, 1400 LST, and 2000 LST, averaged for the BJ, SJZ, CD, and ZJK and sites and the period 7–14 February. As seen in Fig. S6, the temperature in 2020 was higher than that in 2019, by about 10 °C. Compared with 2019, there were strong temperature inversions near the surface for BJ, SJZ, CD, and ZJK (under 950 hPa, 950 hPa, 900 hPa and 850 hPa, respectively) in 2020. This suggests that the atmosphere in 2020 was more stable, which would have been conducive to the accumulation of pollutants. Therefore, these unfavorable meteorological conditions offset the impact of the emissions reduction and contributed to the high PM$_{2.5}$ concentration from 7 to 14 February 2020.

4. Conclusion

In this study, the impacts of the meteorological condition and emissions reduction on the aerosol concentration over the BTH region during the COVID-19 lockdown were analyzed by conducting three numerical experiments with the meteorological field in 2019 and MEIC-2019; the meteorological field in 2020 and MEIC-2019; and the meteorological field in 2020 and MEIC-2020, via the WRF-Chem model. The numerical experiments were performed in 2019 and 2020 for the period 3–16 February, during which a severe fog–haze event (3–16 February 2020) occurred in the BTH region, with a simulated maximum daily PM$_{2.5}$ of 245 μg m$^{-3}$ in Tangshan and 175 μg m$^{-3}$ in Beijing. The main reason for the higher PM$_{2.5}$ from 7 to 14 February 2020 was that the increase in the daily PM$_{2.5}$ caused by the meteorological condition was greater than that caused by the emissions reduction. The difference between the three experiments shows that the daily PM$_{2.5}$ decreased by 5–150 μg m$^{-3}$ due to the emissions reduction and increased by 10–175 μg m$^{-3}$ due to the meteorological condition in Beijing, Shijiazhuang, Cangzhou, Handan, Hengshui, Chengde, Zhangjiakou, and Tangshan from 7 to 14 February.

The horizontal distribution results show that the increase in PM$_{2.5}$ mainly occurred in Beijing, Langfang and Tianjin, with increases of 50–70 μg m$^{-3}$, from 7 to 14 February 2020 relative to that during the same period in 2019. The meteorological condition–induced PM$_{2.5}$ increased by more than 110 μg m$^{-3}$ and the emissions reduction–induced PM$_{2.5}$ decreased by 50–70 μg m$^{-3}$ in Beijing, Langfang and Tianjin. For different aerosol species, the SO$_4^{2-}$, BC, and OC concentrations increased in most areas of BTH, while the NO$_3^-$ and NH$_4^+$ concentrations increased north of the BTH region and decreased south of the BTH region from 7 to 14 February 2020 relative to those during the same period in 2019. The meteorological condition increased the aerosol species concentrations, while the emissions reduction decreased the NO$_3^-$ and NH$_4^+$ concentrations the most and increased the OC concentration from 7 to 14 February 2020. The difference between the meteorological condition of the three experiments shows that the T and RH increased in most regions, the WS decreased in the Zhangjiakou and Chengde areas and changed slightly in other areas of the BTH region, and the PBLH decreased in the BTH region. Simultaneously, compared to 2019, there were temperature inversions near the surface and a more stable atmosphere in 2020. The accumulation of pollutants caused by the unfavorable meteorological conditions offset the decreases caused by the emissions reduction during the COVID-19 lockdown, leading to the high aerosol concentration from 7 to 14 February 2020.

In summary, our study has discussed the reason for the high PM$_{2.5}$ concentration during the COVID-19 lockdown. The results show that the emissions reduction was effective for the reduction of the PM$_{2.5}$ concentration, but it was offset by the unfavorable meteorological condition in some events. Similar results can be found in other studies. For instance, Xu et al. (2018) used the WRF-CMAQ model to simulate the impact of meteorological condition and emissions reduction on PM$_{2.5}$ and showed that the improved meteorological condition in 2016 compared to 2015 reduced PM$_{2.5}$ by 3%, while unfavorable meteorological condition increased PM$_{2.5}$ by 29% in the Pearl River Delta region in 2017. The results of Wang et al. (2019) show that adverse meteorological condition offset the reduction of PM$_{2.5}$ caused by emissions reduction. It should be noted that the uncertainties in the setting of emissions reduction during the COVID-19 lockdown add uncertainties to our research. It is therefore necessary to consider the meteorological condition when assessing the effectiveness of emissions control policies on changes in air pollutants. This may be very helpful for the formulation of future air pollution reduction policies.

Funding

This study was supported by the National Key R&D Program of China (grant number 2017YFB0503901), the National Natural Science Foundation of China (grant numbers 41830109 and 41830966), and the Major Scientific and Technological Innovation Projects of Shandong Province (grant number 2018YJH0901).

Acknowledgments

We acknowledge the free use of the emissions data from the MEIC model (http://www.meicmodel.org).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.aosl.2020.100014.

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