

Impacts of meteorology and emission variations on the heavy air pollution episode in North China around the 2020 Spring Festival

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Abstract Based on the Weather Research and Forecasting model and the Models-3 community multi-scale air quality model (WRF-CMAQ), this study analyzes the impacts of meteorological conditions and changes in air pollutant emissions on the heavy air pollution episode occurred over North China around the 2020 Spring Festival (January to February 2020). Regional reductions in air pollutant emissions required to eliminate the PM_{2.5} heavy pollution episode are also quantified. Our results found that meteorological conditions for the Beijing-Tianjin-Hebei and surrounding “2+26” cities are the worst during the heavy pollution episode around the 2020 Spring Festival as compared with two other typical heavy pollution episodes that occurred after 2015. However, because of the substantial reductions in air pollutant emissions in the “2+26” cities in recent years, and the 32% extra reduction in emissions during January to February 2020 compared with the baseline emission levels of the autumn and winter of 2019 to 2020, the maximum PM_{2.5} level during this heavy pollution episode around the 2020 Spring Festival was much lower than that in the other two typical episodes. Yet, these emission reductions are still not enough to eliminate regional heavy pollution episodes. Compared with the actual emission levels during January to February 2020, a 20% extra reduction in air pollutant emissions in the “2+26” cities (or a 45% extra reduction compared with baseline emission levels of the autumn and winter of 2019 to 2020) could help to generally eliminate regionwide severe pollution episodes, and avoid heavy pollution episodes that last three or more consecutive days in Beijing; a 40% extra reduction in emissions (or a 60% extra reduction compared with baseline emission levels of the autumn and winter of 2019 to 2020) could help to generally eliminate regionwide and continuous heavy pollution episodes. Our analysis finds that during the clean period after the heavy pollution episode around the 2020 Spring Festival, the regionwide heavy pollution episode would only occur with at least a 10-fold increase in air pollutant emissions.

Keywords “2+26” cities, 2020 Spring Festival, Heavy air pollution episode, WRF-CMAQ model

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1. Introduction

Around the 2020 Spring Festival in China from January to February 2020, emissions of air pollutants over North China

has reduced substantially due to the reductions in socio-economic activity levels. However, during this period, two severe air pollution episodes occurred. The contradiction between “relatively low activity levels” and “relatively high pollution levels” has attracted wide attention. Air quality is mainly determined by atmospheric environmental capacity

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and emissions of air pollutants (Cheng and Li, 2010; Chang et al., 2019; Liu et al., 2016; Wang et al., 2014, 2015; Zhang et al., 2012, 2015). From the perspective of environmental management, atmospheric environmental capacity is mainly affected by natural and anthropogenic factors. Natural factors include meteorological conditions, topography, and landforms, etc. Human factors include the regional distribution of pollutant emissions, the composition of air pollutants, and the physical and chemical interaction between different pollutants (Xue et al., 2017; Xu et al., 2018; Wang et al., 2012). From the perspective of chemical mechanisms, Huang et al. (2020a) showed that emission reductions especially NO_x during the 2020 Spring Festival have generally increased the atmospheric oxidation capacity over eastern China. The increased atmospheric oxidation contributed to the formation of secondary aerosols. In Beijing-Tianjin-Hebei and its surrounding areas, which is a relatively small spatial scale, meteorological conditions have an important impact on the atmospheric environmental capacity because the topography and landforms and the spatial distribution of air pollutant emissions would not change substantially in the short term. Therefore, this study analyzes the heavy air pollution episodes from the perspectives of meteorological conditions and air pollutant emissions.

Several questions have been the focus of the scientific community and the public: what are the meteorological conditions during the heavy pollution episode around the 2020 Spring Festival compared with other typical heavy pollution episodes; how much pollutant emissions still need to be reduced to substantially improve air quality; what is the difference in atmospheric environmental capacity between the pollution episodes and the following clean period around the 2020 Spring Festival. Constrained by a specific air quality target, this study uses the comprehensive emission reduction requirements of major air pollutants to characterize the atmospheric environmental capacity. We explore the cause of the two heavy pollution episodes over the Beijing-Tianjin-Hebei and surrounding “2+26” cities around the 2020 Spring Festival, with focuses on the impacts of meteorological conditions and the comprehensive emission reduction requirements of major air pollutants.

Scholars have carried out a lot of works to study the impact of meteorological conditions on air quality (Lü et al., 2019; Lin et al., 2019; Chen et al., 2017; Chuang et al., 2017; Kozáková et al., 2017; Liu et al., 2017; Wu et al., 2017; Zhang et al., 2012). Zhang et al. (2016) studied the impact of meteorological conditions on air quality in the Beijing-Tianjin-Hebei region over the past 30 years from the perspective of weather type classification; Liu et al. (2017) used a numerical model to quantify the impact of meteorological conditions on PM_{2.5} pollution in the Beijing-Tianjin-Hebei region; Xu et al. (2019) quantitatively analyzed the impacts of meteorological conditions and air pollutant emissions on

PM_{2.5} pollution across China and over the key regions based on the WRF-CMAQ modelling system. Huang et al. (2020b) found that under specific meteorological conditions, the interaction of long-range transport and aerosol-boundary layer feedback would aggravate the transboundary transportation of air pollution between China's two large urban agglomerations: the Beijing-Tianjin-Hebei region and the Yangtze River Delta region. However, few studies have comparatively analyzed the meteorological conditions during different typical heavy pollution episodes. Studies have also investigated the requirements of air pollutant emission reductions under different air pollution control objectives. Ren et al. (2000) quantified the maximum allowable SO₂ emissions constrained by the national standard of annual average SO₂ concentrations. Xue et al. (2014) simulated and calculated the maximum allowable emissions of major air pollutants in China with a constrain of the national standard for annual average PM_{2.5} concentrations (GB3095-2012). Wang et al. (2016) developed a three-dimensional iterative algorithm for estimating the atmospheric capacity of multiple air pollutants. Yet, few studies have analyzed the maximum allowable emissions of major air pollutants and the required emission reductions for typical short term heavy pollution episodes.

The WRF-CMAQ model has been widely used in meteorological condition simulations and air quality simulations (Hu et al., 2016). This study conducts the following analyses based on the WRF-CMAQ modelling system. (1) Impacts of unfavorable meteorological conditions and reductions in air pollutant emissions on PM_{2.5} concentrations: three typical heavy pollution episodes (including an episode around the 2020 Spring Festival) in the “2+26” city after the year 2015 are selected; the sensitivity test method of “varying meteorological conditions with fixed emissions” is applied to reveal the impact of meteorological conditions on the heavy pollution episodes around the 2020 Spring Festival, which further supports the analysis of the impacts of emission variations on the heavy pollution episodes. (2) Analysis of requirements for emission reductions: targeting the heavy pollution episodes around the 2020 Spring Festival, different emission reduction ratios are set to estimate the emission reductions required to generally eliminate regional heavy pollution episodes. (3) Analysis of the difference in atmospheric environmental capacity between the pollution episode and the clean period around the 2020 Spring Festival: targeting a clean period after the heavy pollution episode around the 2020 Spring Festival, different emission increment ratios are set to quantify the difference in atmospheric environmental capacity between the pollution episode and the clean period. This study for the first time reveals the reasons for the heavy pollution episode around the 2020 Spring Festival from the perspective of meteorological conditions and emission reduction require-

ments. It is of great significance to guide the management of the atmospheric environment and the response to heavy pollution episodes.

2. Data and method

The model simulation domain covers the whole China, with a focus on the Beijing-Tianjin-Hebei and surrounding “2+26” cities.

2.1 Data source

2.1.1 Emission inventory of air pollutants

Emissions of SO_2 , NO_x , particulate matters (PM_{10} , $\text{PM}_{2.5}$, and their compositions), NH_3 , and volatile organic compounds (VOCs; containing multiple chemical compositions) and other pollutants are required as the inputs to the CAMQ model. In this study, the initial air pollutant emission inventory is retrieved from the 2017 Multi-resolution Emission Inventory for China (MEIC, <http://www.meicmodel.org>). These anthropogenic emissions of SO_2 , NO_x , PM_{10} , $\text{PM}_{2.5}$, BC, OC, NH_3 , and VOCs around the 2020 Spring Festival (January to February 2020) are then iteratively corrected based on the observed $\text{PM}_{2.5}$ concentrations. Biogenic emissions of VOCs are calculated using the Model of Emissions of Gases and Aerosols from Nature model (MEGAN; Guenther et al., 2006). The basic assumption of the iterative correction of the emission inventory is that, under the condition that changes in emissions are small, the non-linear relationship between emissions and $\text{PM}_{2.5}$ concentrations can be approximated as a series of linear relationships over small segments (Xue et al., 2014). Based on this assumption, the city-specific ratios between the simulated $\text{PM}_{2.5}$ concentration and the observed $\text{PM}_{2.5}$ concentration can be used as weighting coefficients to formulate a city-specific strategy for emission inventory correction (Xue et al., 2014). Multiple iterations of the corrections are conducted based on the air quality model until the differences between the simulated $\text{PM}_{2.5}$ concentrations and the observed $\text{PM}_{2.5}$ concentrations in the “2+26” cities are less than 10% (Xue et al., 2014). We then obtain the final emission inventory of air pollutants. In this study, the observation data from October 2019 to December 2019 is set as the

constraint target, and the baseline emission inventory of major air pollutants in the autumn and winter of 2019 to 2020 (“baseline” emission inventory for 2019-2020 cold season) is obtained through iterative corrections. The observation data during January to February 2020 is then set as a constraint target, and the emission inventory of major air pollutants around the 2020 Spring Festival (“epidemic” emission inventory) is further obtained through iterative corrections. The difference between the simulated $\text{PM}_{2.5}$ concentration over the “2+26” cities based on the final “epidemic” emission inventory and the observed $\text{PM}_{2.5}$ concentrations around the 2020 Spring Festival is about 8%. The emissions are corrected using the following equations.

$$E_{ij} = E_{i-1,j} \times \frac{C_{m,j}}{C_{s(i-1,j)}}, \quad (1)$$

$$\left| \frac{C_m - C_s}{C_m} \right| \leq 10\%, \quad (2)$$

where i represents times of iteration; j represents one of the “2+26” cities; E_{ij} represents air pollutant emissions for city j after i times of iteration (unit: kg d^{-1}); $E_{i-1,j}$ represents air pollutant emissions for city j after $i-1$ times of iteration (unit: kg d^{-1}); $C_{m,j}$ represents observed $\text{PM}_{2.5}$ concentration in city j (unit: $\mu\text{g m}^{-3}$); $C_{s(i-1,j)}$ represents simulated $\text{PM}_{2.5}$ concentration after $i-1$ times of iteration on the emission inventory ($\mu\text{g m}^{-3}$). In eq. (2), C_m represents the mean observed $\text{PM}_{2.5}$ concentrations over the “2+26” cities (unit: $\mu\text{g m}^{-3}$); C_s represents the mean simulated $\text{PM}_{2.5}$ concentrations over the “2+26” cities (unit: $\mu\text{g m}^{-3}$).

2.1.2 Air quality monitoring data

The air quality monitoring data are collected from the Data Center of the Ministry of Ecology and Environment of the People’s Republic of China. Daily mean $\text{PM}_{2.5}$ concentrations of the Beijing-Tianjin-Hebei and surrounding “2+26” cities are collected.

2.2 Model configuration

2.2.1 Simulation periods

By analyzing the daily mean $\text{PM}_{2.5}$ concentration from January 2015 to February 2020, this study selects three typical heavy pollution episodes and a clean period after the heavy pollution episode around the 2020 Spring Festival (Table 1)

Table 1 Different cases considered in this study

Case name	Simulation period	Analysis period	Observed mean $\text{PM}_{2.5}$ levels in heavily or more polluted days ($\mu\text{g m}^{-3}$)
Episode around the 2020 Spring Festival (case 1)	2020-01-19–2020-02-15	2020-01-22–2020-02-14	195
Episode around 2017 New Year’s Day (case 2)	2016-12-13–2017-01-14	2016-12-16–2017-01-14	240
Episode around 2015 Christmas Day (case 3)	2015-12-15–2015-12-26	2015-12-18–2015-12-26	284
Clean period during the 2020 Spring Festival (case 4)	2020-02-12–2020-02-17	2020-02-15–2020-02-17	–

to analyze the causes of the heavy pollution episode around the 2020 Spring Festival. Three days of spin-up is applied to the simulations of all cases.

2.2.2 Model domain

The CMAQ model in this study is based on a Lambert projection with an origin of 103°E, 37°N, and two parallel latitudes of 25°N and 40°N. The horizontal simulation range is −2690–2690 km over the *X* direction and −2150–2150 km over the *Y* direction. The grid spacing is set to 20 km, and the study domain is divided into 270×216 grid cells in total. Vertically, 14 pressure layers are set with the layer spacing gradually increases from bottom to top (Xu et al., 2017).

2.2.3 Meteorological simulations

The meteorological field required by the CMAQ model is provided by the Weather Research and Forecasting model (WRF). The WRF model and the CMAQ model use the same simulation time period and spatial projection coordinate system. In the WRF model, a total of 35 pressure layers are set in the vertical direction, and the layer spacing gradually increases from bottom to top. The meteorological initial and boundary conditions are provided by the global reanalysis data from the National Centers for Environmental Prediction Final Analysis (NCEP-FNL) (<http://rda.ucar.edu/datasets/ds083.2/>), with a temporal resolution of 6h and the spatial resolution of 1°. The WRF model is restarted every day and each simulation is run for 30h, with the first 6h as the spin-up. The NCEP Automated Data Processing (ADP) observation data (<http://rda.ucar.edu/datasets/ds461.0/>) are used for objective analysis and data assimilation.

2.2.4 Model evaluation

The models used in this study are configured following previous studies (Xu et al., 2017; Xue et al., 2014). In the four cases of analysis, the meteorological conditions and pollutant emissions are consistent in time only in case 1 and case 4. We therefore only compare simulated PM_{2.5} concentrations in case 1 and case 4 with the observed PM_{2.5} concentrations. Based on the “Guidelines for selection of

ambient air quality models (on trial)”, normalized mean bias (NMB), normalized mean error (NME), and the correlation coefficient (*r*) are used as parameters to test the model performance. The criteria for PM_{2.5} are $-50\% < \text{NMB} < 80\%$, $\text{NME} < 150\%$, $R^2 > 0.3$. Figure 1 shows the comparison between simulated and observed PM_{2.5} concentrations. Table 2 documents the results for the considered statistical parameters, where *n* represents the sample number of data pairs in the “2+26” cities during the analysis period. In case 1 that uses the “baseline” emission inventory for the 2019–2020 cold season, the correlation coefficient between simulated and observed PM_{2.5} concentrations is 0.59, and NMB and NME of the simulated PM_{2.5} concentrations are 33.75%, 47.90%, with the simulated PM_{2.5} concentrations substantially higher than the observed values. In case 1 and case 4 that uses the “epidemic” emission inventory, the correlation coefficients, NMB, and NME are 0.60, 7.00%, 35.14%, respectively, for case 1, and are 0.61, −0.34%, and 24.90%, respectively, for case 4. These evaluation results show that cases use the “epidemic” emission inventory outperform the case that uses the “baseline” emission inventory for the 2019–2020 cold season, indicating that the “epidemic” emission inventory obtained in this study by the iterative correction is reliable and the model performance is acceptable.

3 Results and discussion

3.1 Impacts of meteorological conditions on the heavy pollution episode around the 2020 Spring Festival

The atmospheric self-cleaning ability index (ASI) can be used to characterize the ability of meteorological conditions to remove air pollutants. The higher the ASI value, the stronger the atmospheric self-cleaning ability (Zhu et al., 2018). The average ASI can characterize the average meteorological conditions during the simulation period. But this average ASI does not well characterize the short-term abrupt extreme adverse meteorological conditions, which are the major reason for the occurrence of heavy pollution episodes.

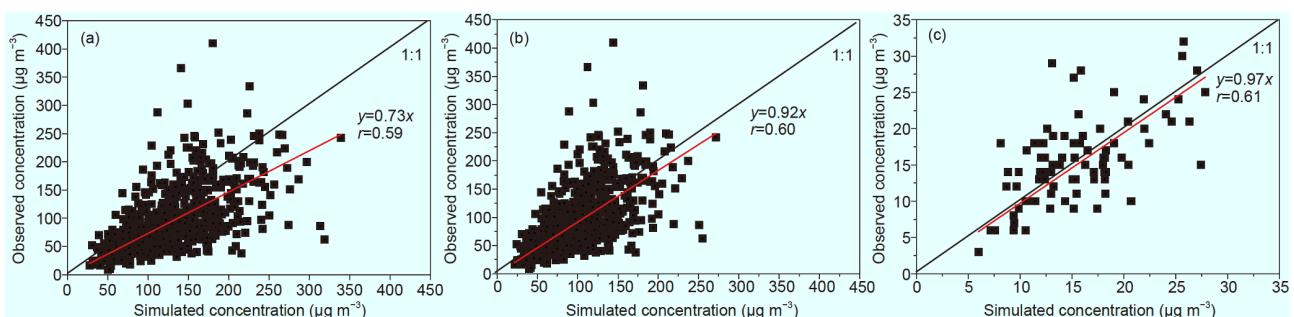


Figure 1 Correlation between simulated and observed PM_{2.5} concentrations. (a) Results for case 1 based on the “baseline” 2019–2020 cold season emission inventory; (b) results for case 1 based on the “epidemic” emission inventory; (c) results for case 4 based on the “epidemic” emission inventory.

Table 2 Statistics on the evaluation of simulated PM_{2.5} concentrations^{a)}

	<i>n</i>	<i>r</i>	NMB	NME
Case 1	672	0.59	33.75%	47.90%
Case 1 [*]	672	0.60	7.00%	35.14%
Case 4	84	0.61	-0.34%	24.90%

a) Case 1, simulation is based on the “baseline” 2019–2020 cold season emission inventory; case 1^{*}, simulation is based on the “epidemic” emission inventory; case 4, simulation is based on the “epidemic” emission inventory

The minimum value of daily ASI, however, characterizes the short-term extreme adverse meteorological conditions during the simulation period. For this reason, based on WRF-simulated meteorological parameters, including boundary layer height, wind speed, and precipitation, this study calculates the average value and minimum daily value of ASI during the simulation period for case 1, case 2, and case 3 (Figures 2 and 3). Based on the period average value of ASI,

compared with case 2 and case 3, the averaged meteorological conditions are not the worst in case 1 (Figure 2). However, based on the minimum daily value of ASI, the self-cleaning ability of case 1 and case 2 are similar in magnitude, much worse than that of case 3.

ASI can be used to estimate the atmospheric self-cleaning ability based on a few meteorological parameters. However, what ASI characterizes is the “static self-cleaning ability”, which cannot characterize the dynamic transport effect of air pollutants in an area driven by the meteorological conditions. Therefore, in addition to the ASI analysis, we further use the WRF-CMAQ model to compare the meteorological conditions in case 1, case 2, and case 3, by using the sensitivity test method of “varying meteorological conditions with fixed emissions” (Figure 4). On the regional average basis, with the same air pollutant emissions, the daily maximum PM_{2.5} concentration in case 1 is estimated to be 271 $\mu\text{g m}^{-3}$, higher than the maximum values in case 2 and case 3 (Table 3). In case 1, the average PM_{2.5} concentration for days that are

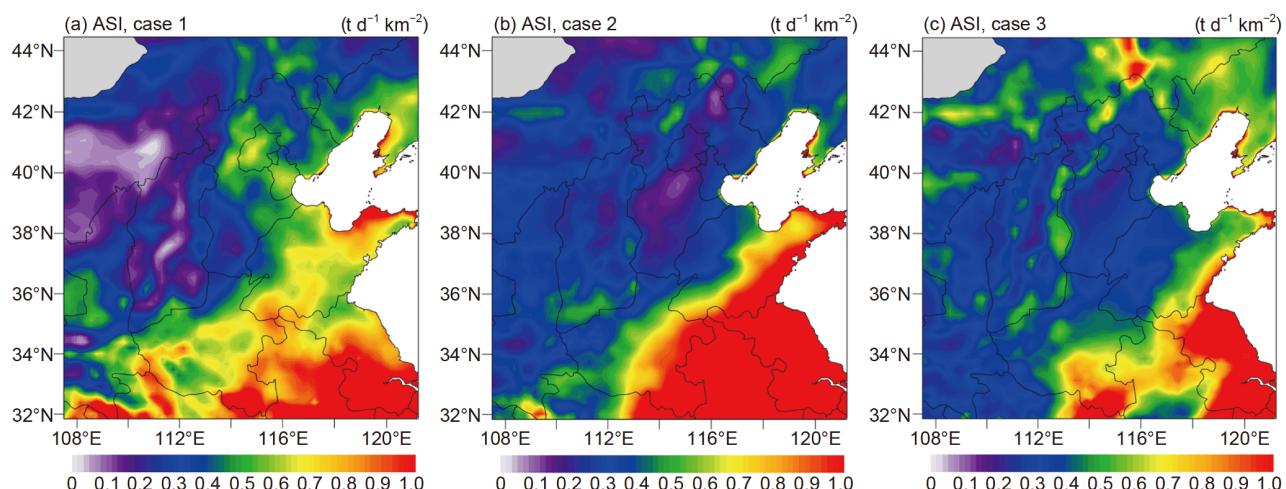


Figure 2 The average value of atmospheric self-cleaning ability index (ASI). (a) Case 1; (b) case 2; (c) case 3.

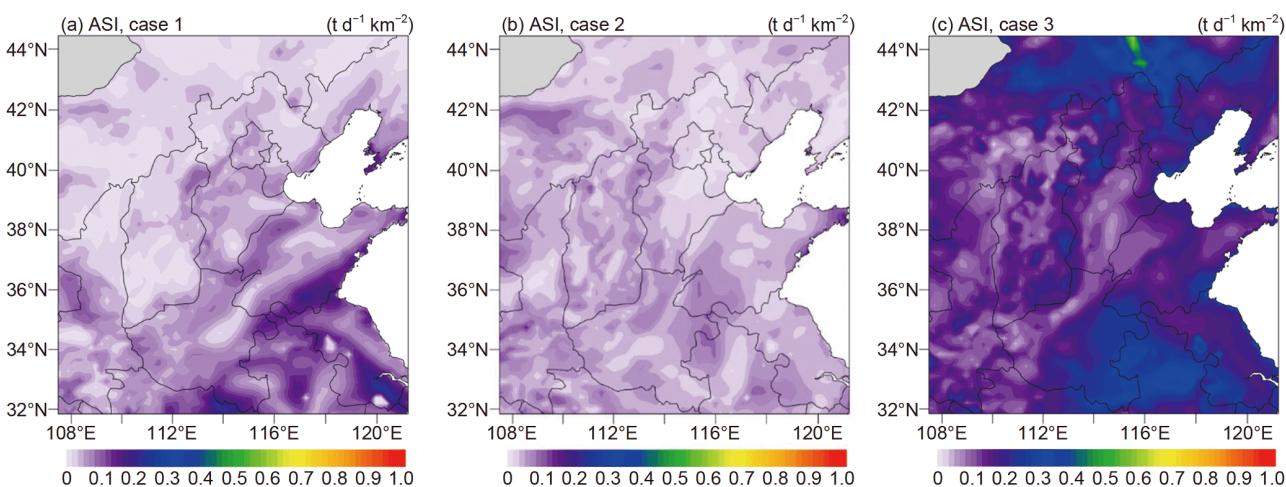


Figure 3 Minimum daily value of atmospheric self-cleaning ability index (ASI). (a) Case 1; (b) case 2; (c) case 3.

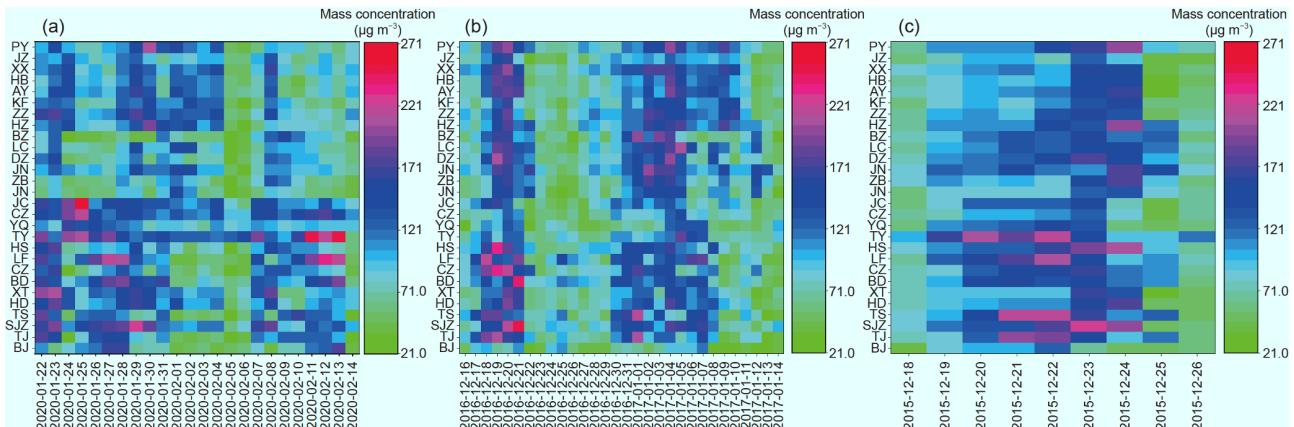


Figure 4 Simulated PM_{2.5} concentrations based on fixed air pollutant emission inventory ($\mu\text{g m}^{-3}$). (a) Meteorological conditions in case 1: episode occurred around the 2020 Spring Festival; (b) Meteorological conditions in case 2: episode occurred around New Year's Day in 2017; (c) Meteorological conditions in case 3: episode occurred around Christmas Day in 2015. Emissions intensity of air pollutants are fixed at case 1 levels in all the simulations. BJ, Beijing; TJ, Tianjin; SJZ, Shijiazhuang; TS, Tangshan; HD, Handan; XT, Xingtai; BD, Baoding; CZ, Cangzhou; LF, Langfang; HS, Hengshui; TY, Taiyuan; YQ, Yangquan; CZ, Changzhi; JC, Jincheng; JN, Jinan; ZB, Zibo; JN, Jining; DZ, Dezhou; LC, Liaocheng; BZ, Binzhou; HZ, Heze; ZZ, Zhengzhou; KF, Kaifeng; AY, Anyang; HB, Hebi; XX, Xinxiang; JZ, Jiaozuo; PY, Puyang.

Table 3 Statistics on the simulated PM_{2.5} concentrations based on fixed air pollutant emission inventory^{a)}

Regional results	Case 1 ($\mu\text{g m}^{-3}$)	Case 2 ($\mu\text{g m}^{-3}$)	Case 3 ($\mu\text{g m}^{-3}$)
Maximum daily mean value	271	247	224
Mean value for moderately or more polluted days	147	151	151
Mean value for heavily or more polluted days	180	174	177

a) Because we use fixed emission inventory for these simulations, the simulated PM_{2.5} concentrations are not comparable with the observed values. The relative magnitude of the simulated PM_{2.5} concentrations in different scenarios characterizes the impacts of meteorological conditions. Emissions intensity of air pollutants are fixed at case 1 levels in all the simulations.

moderately or more polluted is estimated as $147 \mu\text{g m}^{-3}$; results for days that are heavily or more polluted is estimated as $180 \mu\text{g m}^{-3}$, higher than that in case 2 and case 3. The maximum daily PM_{2.5} concentrations in Beijing are estimated as 172, 116, and $125 \mu\text{g m}^{-3}$, respectively, for case 1, case 2, and case 3. The sensitivity test based on the “varying meteorological conditions with fixed emissions” approach indicates that the meteorological conditions of the heavy pollution episode occurred around the 2020 Spring Festival are the worst among the three typical heavy pollution episodes after 2015.

3.2 Threshold for regional emissions to eliminate heavy pollution episodes under unfavorable meteorological conditions

In this section, we focus on case 1, the case with the worst meteorological conditions that occurred around the 2020 Spring Festival. We analyze to what extent should the emissions be reduced to generally eliminate the regionwide and continuous heavy pollution episodes. In this research, we define that avoiding the simultaneous occurrence of severe pollution episodes in three or more cities is regarded as a sign of generally eliminating regionwide severe pollution.

Avoiding the simultaneous occurrence of heavy or severe pollution episodes in five or more cities and avoiding heavy or severe pollution episodes that last three or more consecutive days in any cities are regarded as the sign of generally eliminating regionwide and continuous heavy pollution episodes (Table 4). The heavy pollution episodes are mainly caused by physical transport and chemical reactions of regional air pollutant emissions. Therefore, regionwide joint emission controls are necessary to tackle the heavy pollution episodes. We thus set a baseline scenario and seven regional emission reduction scenarios for cases 1 to test emission reductions required to eliminate the heavy pollution episode occurred around the 2020 Spring Festival. The seven emission reduction scenarios are configured with regional air pollutant emission, reduced by 20%, 30%, 40%, 50%, 60%, 70%, and 80%, respectively. The relative ratios of PM_{2.5} reductions in the seven emission reduction scenarios compared with the baseline scenario are acquired based on the WRF-CMAQ model. To reduce the systematic uncertainty introduced by the WRF-CMAQ model, the quantified relative reduction ratio is then applied to the observed PM_{2.5} concentration, and the corrected (observation-based) PM_{2.5} concentrations in each of the seven emission reduction scenarios are then derived. Figure 5 shows the simulated PM_{2.5}

Table 4 Statistics on the pollution levels in scenarios with different emission reduction ratios during the heavy pollution episode around the 2020 Spring Festival

Emission reduction ratio	Times severe pollution occurred simultaneous in three or more cities	Times heavy or severe pollution occurred simultaneous in five or more cities	Times heavy or severe pollution last three or more consecutive days in one city	Number of heavily or more polluted days	Number of moderately or more polluted days	Number of slightly or more polluted days
0	1	8	15	113	187	375
20%	1	5	6	59	139	289
30%	0	2	1	37	104	239
40%	0	1	1	19	64	187
50%	0	0	0	6	33	147
60%	0	0	0	3	11	90
70%	0	0	0	1	4	41
80%	0	0	0	0	1	6

concentrations on February 8, 2020, in different emission reduction scenarios: the larger the emission reduction ratio, the lower the PM_{2.5} concentrations. The simulation results (**Table 4**) indicate that, a 20% reduction in air pollutant emissions during January to February 2020 could generally eliminate regionwide severe pollution episodes. A 40% reduction in air pollutant emissions during January to February 2020 could generally eliminate regionwide and continuous heavy pollution episodes. Yet local heavy pollution episodes may still occur over some cities. Therefore, while strengthening regional joint prevention and control, we should still pay attention to local emission reductions in specific cities.

During January to February 2020, no severe pollution episodes occurred in Beijing. During this period, six heavily polluted days occurred in Beijing, and the number of heavy pollution episodes lasts three or more consecutive days is two. The simulation results indicate that, more than 20% reductions in emissions over the “2+26” cities can help Beijing to avoid heavy pollution episodes that last three or more consecutive days during January to February 2020.

3.3 The maximum allowable regional air pollutant emissions under favorable meteorological conditions

The atmospheric environmental capacity or the maximum allowable air pollutant emissions under a specific air quality target changes substantially along with the changes in meteorological conditions. To explore the differences in the atmospheric environmental capacity between the heavy pollution episode and the clean period around the 2020 Spring Festival, this section focuses on a clean period (February 15–17, 2020; snowy and windy days) after the heavy pollution episode. The anthropogenic emission used here is the same as that used in section 3.2, which is the “epidemic” emission inventory obtained by the iterative correction approach. For this clean period, we also set a baseline scenario and seven emission increment scenarios: emissions of air pollutants are multiplied by 2, 3, 4, 5, 10, 15,

20, respectively. The relative ratio of PM_{2.5} increment in the seven emission increment scenarios compared with the baseline scenario are acquired by the WRF-CMAQ model. To reduce the systematic uncertainty introduced by the WRF-CMAQ model, the quantified relative increment ratio is then applied to the observed PM_{2.5} concentration, and the corrected (observation-based) PM_{2.5} concentrations in each of the seven emission increment scenarios are then derived. **Figure 6** shows the simulated PM_{2.5} concentrations on February 16, 2020, in different emission increment scenarios. The simulation results show that in this typical clean period, moderate pollution only occurs in a few cities when the emissions are multiplied by 5; regionwide heavy pollution episodes would occur only when the emissions are multiplied by 10 (**Table 5**).

3.4 Discussion

Daily emissions of SO₂, NO_x, and PM_{2.5} for the “2+26” cities from October to December 2017 are estimated as 5183, 11127, and 5833 tons, respectively, according to the MEIC model. These values are corrected to 3467, 9406, and 4333 tons, respectively, for the period October to December 2019 based on our iterative correction approach. The average reduction rate for these air pollutants is about 25% in two years. These corrected values are used to represent the “baseline” emission inventory for the 2019–2020 cold season. These “baseline” 2019–2020 cold season emission intensity is further corrected based on the observed PM_{2.5} during January to February 2020. The results show that the daily emissions of SO₂, NO_x, and PM_{2.5} during January to February 2020 are estimated as 2358, 6396, 2946 tons, respectively, about 32% lower than the “baseline” 2019–2020 cold season emissions. Emission reductions are estimated to have reduced the PM_{2.5} concentrations averaged over January 22nd to February 14th, 2020 (case 1) by 27% as compared with the “baseline” 2019–2020 cold season emission situation.

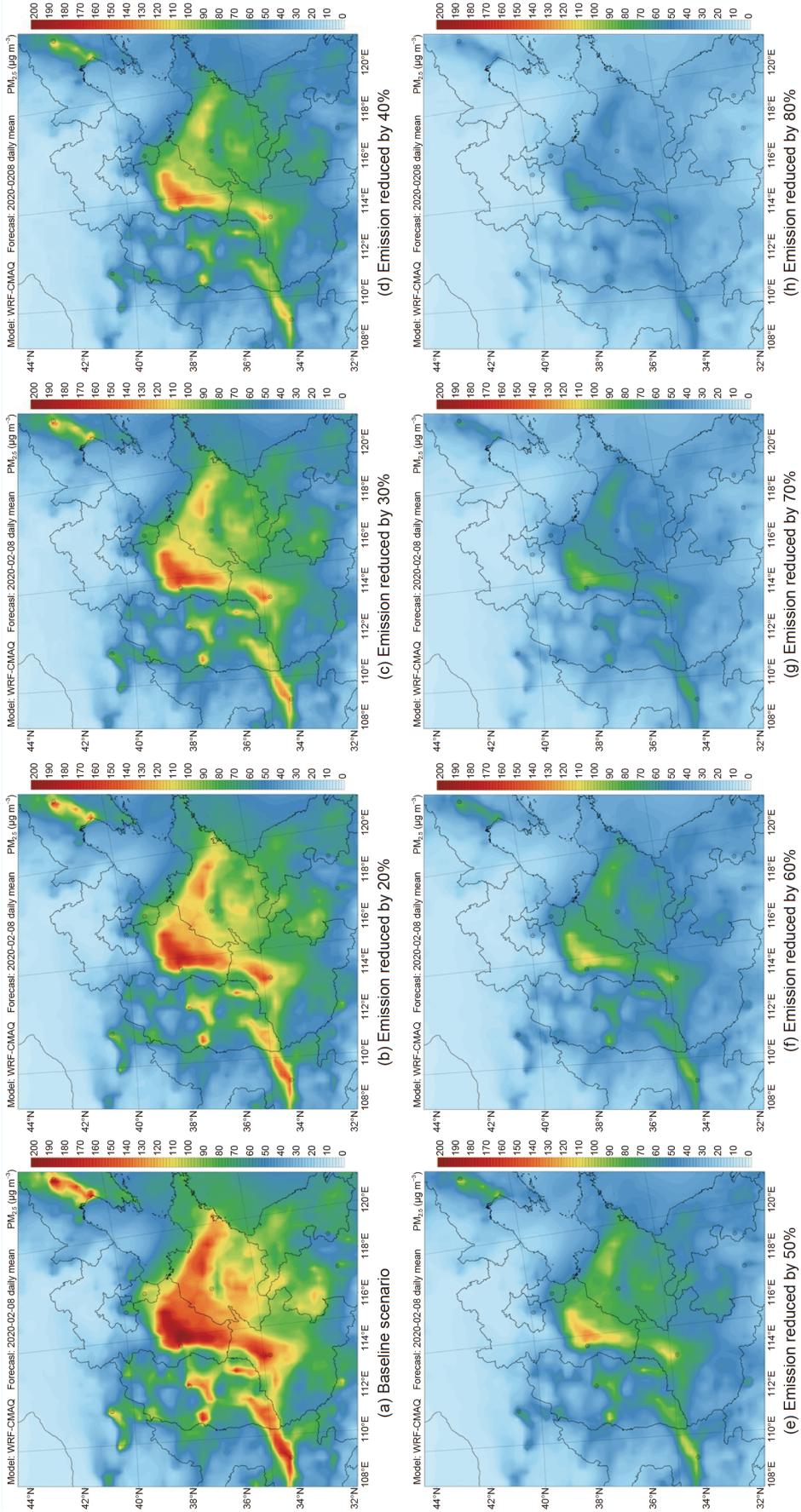


Figure 5 Simulated $\text{PM}_{2.5}$ concentrations in scenarios with different emission reduction ratios during the heavy pollution episode around the 2020 Spring Festival ($\mu\text{g m}^{-3}$).

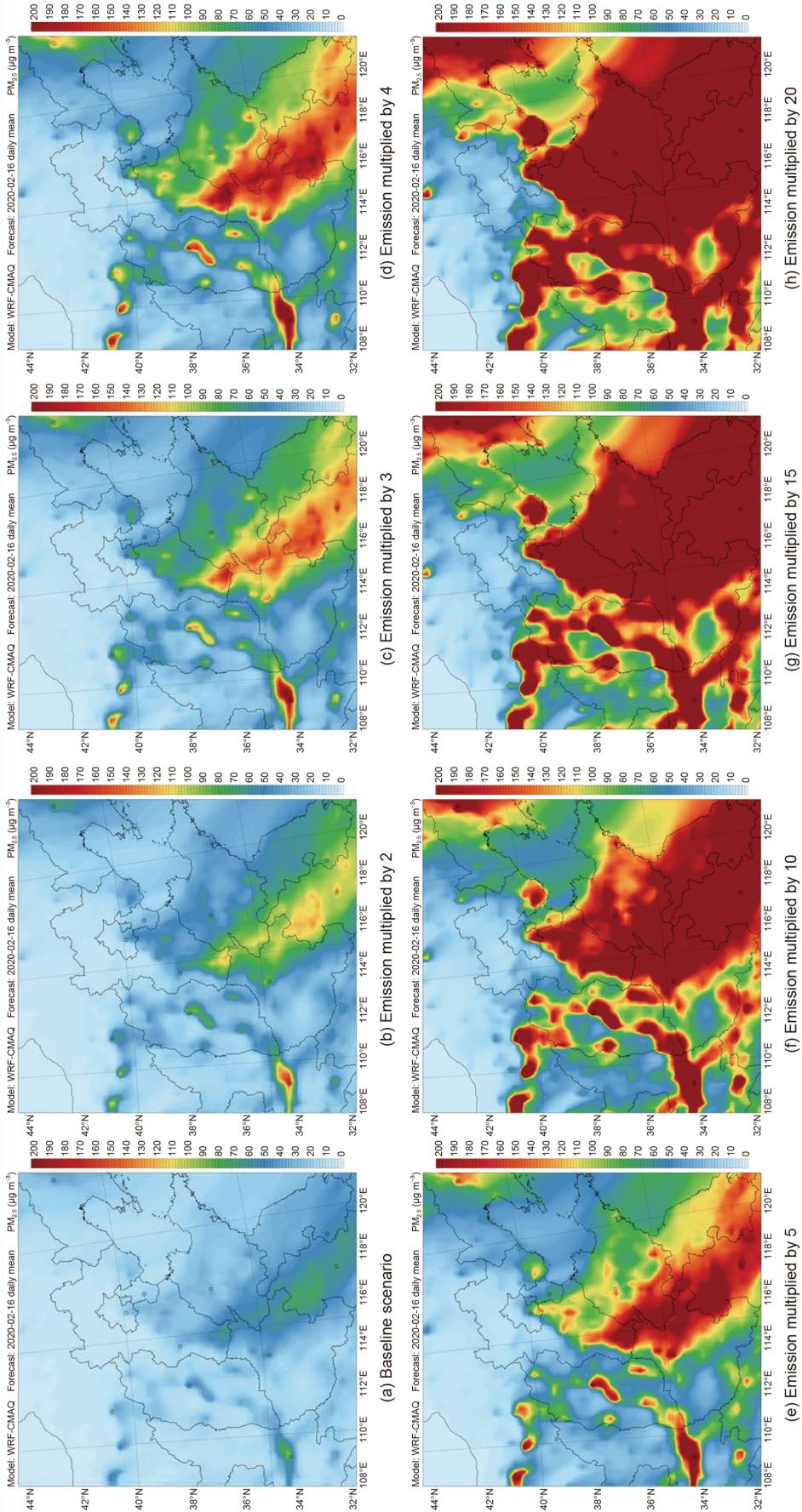


Figure 6 Simulated $\text{PM}_{2.5}$ concentrations in scenarios with different emission increment ratios during the 2020 Spring Festival ($\mu\text{g m}^{-3}$).

Table 5 Statistics on the pollution levels in scenarios with different emission increment ratios during the clean period around the 2020 Spring Festival

Emissions multiply by	Times heavy or severe pollution occurred simultaneous in five or more cities	Times heavy or severe pollution last three or more consecutive days in one city	Number of heavily or more polluted days	Number of moderately or more polluted days	Number of slightly or more polluted days
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	1
4	0	0	0	1	7
5	0	0	0	2	16
10	1	0	14	36	66
15	3	8	47	66	78
20	3	19	66	76	80

Studies by the National Joint Research Center for Tackling Key Problems in Air Pollution Control also found that emissions of SO₂, NO_x, PM_{2.5}, and VOCs in the “2+26” cities have reduced by 20–30% during the 2020 Spring Festival (http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202002/t20200211_762584.html). Among major emission sectors, emissions from vehicle and fugitive dust have decreased notably; emissions from thermal power plants and the iron and steel industry have decreased by about 10%; but emissions from coking, petrochemical, glass, and nonferrous industries, and other industries show no notable trend. In some of the rural areas, coal has been substituted by natural gas and electricity. However, there are still more than 10 million households are burning coal for heating in the winter. Observational data also shows that CO concentration, which is an indicator of the amount of coal burned, has increased in rural areas, indicating that the emissions from civil bulk coal consumption have not decreased.

Meteorological conditions in case 1, the heavy pollution episode around the 2020 Spring Festival, are the most unfavorable compared with case 2 (the pollution episode occurred around New Year’s Day in 2017) and case 3 (the pollution episode occurred around Christmas Day in 2015). The atmospheric environmental capacity is also the lowest in case 1. If air pollutant emissions are the same in the three cases, air pollution levels in case 1 would be the highest. However, due to the substantial reductions in air pollutant emissions in the “2+26” cities in recent years, the actual air pollution level in case 1 is much lower than in case 2 and case 3. In case 1, the observed maximum daily mean PM_{2.5} concentrations, mean PM_{2.5} concentrations in moderately or more polluted days, and mean PM_{2.5} concentrations in heavily or more polluted days are 47.2%, 19.8%, and 18.7% lower than the air pollution episode occurred around New Year’s Day in 2017 (case 2), respectively. Therefore, reducing air pollutant emissions is the main driving factor in improving air quality and reducing the occurrence frequency of heavy pollution episodes.

In addition, analysis of the clean period around the 2020

Spring Festival (case 4) has shown that at least a 10-fold increase in air pollutant emissions could result in a regionwide heavy pollution episode. On the other hand, analysis of the heavy pollution episode around the 2020 Spring Festival (case 1) shows that to eliminate the regionwide and continuous heavy pollution episodes, air pollutant emissions have to be reduced by 40% compared with the “epidemic” emission levels, or by 60% compared with the “baseline” 2019–2020 cold season emission levels. The “epidemic” emission levels are only 32% lower than the “baseline” 2019–2020 cold season emission, smaller than the required 60% reductions in emissions. This unmet requirement in emission reductions is the fundamental reason for the occurrence of the heavy pollution episode around the 2020 Spring Festival.

4. Conclusion

(1) Meteorological conditions for the “2+26” cities are the worst during the heavy pollution episode around the 2020 Spring Festival as compared with two other typical heavy pollution episodes that occurred after 2015.

(2) During January to February 2020, compared with the actual emission levels, a 20% reduction in air pollutant emissions could help to generally eliminate regionwide severe pollution episodes, and avoid heavy pollution episodes that last three or more consecutive days in Beijing; a 40% reduction in emissions could help to generally eliminate regionwide and continuous heavy pollution episodes.

(3) During the clean period after the heavy pollution episode around the 2020 Spring Festival, the regionwide heavy pollution episode would only occur with at least a 10-fold increase in air pollutant emissions.

(4) The unfavorable meteorological condition is an important external cause of the heavy pollution episode in the “2+26” cities around the 2020 Spring Festival. And the far exceeding of air pollutant emissions than the atmospheric environmental capacity is the main internal cause of the

heavy pollution episode. Emissions of major air pollutants during the epidemic have been reduced substantially and have effectively suppressed the spatial extent and intensity of the heavy pollution episode. However, air pollutant emissions during the epidemic are only 32% lower than the “baseline” emission levels during the 2019–2020 cold season, while at least 60% reductions in emissions are required to generally eliminate regionwide and continuous heavy pollution episodes.

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