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Large contributions of emission reductions and meteorological conditions to the abatement of PM_{2.5} in Beijing during the 24th Winter Olympic Games in 2022

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A B S T R A C T

To guarantee the blue skies for the 2022 Winter Olympics held in Beijing and Zhangjiakou from February 4 to 20, Beijing and its surrounding areas adopted a series of emission control measures. This provides an opportunity to determine the impacts of large-scale temporary control measures on the air quality in Beijing during this special period. Here, we applied the WRF-CMAQ model to quantify the contributions of emission reduction measures and meteorological conditions. Results show that meteorological conditions in 2022 decreased PM_{2.5} in Beijing by 6.9 and 11.8 $\mu\text{g}/\text{m}^3$ relative to 2021 under the scenarios with and without emission reductions, respectively. Strict emission reduction measures implemented in Beijing and seven neighboring provinces resulted in an average decrease of 13.0 $\mu\text{g}/\text{m}^3$ (-41.2%) in PM_{2.5} in Beijing. Over the entire period, local emission reductions contributed more to good air quality in Beijing than nonlocal emission reductions. Under the emission reduction scenario, local, controlled regions, other regions, and boundary conditions contributed 47.7%, 42.0%, 5.3%, and 5.0% to the PM_{2.5} concentrations in Beijing, respectively. The results indicate that during the cleaning period with the air masses from the northwest, the abatements of PM_{2.5} were mainly caused by local emission reductions. However, during the

potential pollution period with the air masses from the east-northeast and west-southwest, the abatements of PM_{2.5} were caused by both local and nonlocal emission reductions almost equally. This implies that regional coordinated prevention and control strategies need to be arranged scientifically and rationally when heavy pollution events are forecasted.

Introduction

Rapid industrialization and urbanization have resulted in the discharge of a large amount of pollutants into the atmosphere, causing severe haze episodes to occur frequently in China, especially in the most densely populated and economically developed areas, such as the Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD), and Pearl River Delta (PRD) regions (Zhang and Cao, 2015; Ye et al., 2018; Guo et al., 2020; Wang et al., 2021b). PM_{2.5} refers to particles with an aerodynamic diameter less than 2.5 μm, which are a major contributor to the formation of haze. Many studies have proved that high PM_{2.5} concentrations can seriously harm human health through respiratory diseases, cause traffic problems due to the reduced visibility, and affect the weather and climate directly and indirectly (Guo et al., 2014; Hao et al., 2017; Liu et al., 2022; Tian et al., 2022).

As the capital city of China, Beijing has received extensive attention due to its unfavorable topographical conditions, large pollutant emissions, and the impacts of regional pollutant transports (Wu et al., 2017; Wang et al., 2019; Huang et al., 2021; Wang et al., 2021a). In September of 2013, in response to the unprecedented severe haze, the State Council issued “The Air Pollution Prevention and Control Action Plan”, aiming to reduce the concentrations of PM_{2.5} in the BTH, YRD, and PRD regions by 25%, 20%, and 15%, respectively, by 2017, with the average annual PM_{2.5} concentration in Beijing controlled at around 60 μg/m³ (Jin et al., 2016). Since extreme haze episodes have occasionally occurred, causing premature deaths and huge economic losses, China has adopted stricter policies and set higher goals to improve air quality and protect people’s health (Gao et al., 2017a). After 5 years of great efforts across the country, the average annual PM_{2.5} concentrations in Beijing dropped to 58 μg/m³ in 2017, successfully completing the task (Wen et al., 2021). At present, China is carrying out the environmental protection work during the 14th Five-Year Plan, and strives to promote the coordinated emission reductions of multiple air pollutants, so as to achieve the synergistic effects of reducing pollution and carbon. This study is conducted under this background.

Because of its well-known international influence, Beijing has undertaken many high-standard international reception tasks and hosted many mega events, including the 2008 Beijing Olympic Games, the 2014 APEC Summit, and the 2015 Grand Military Parade (Ma et al., 2020). Based on the measurements, aerosol spatiotemporal characteristics, pollutant sources and influencing factors of blue skies in these events have been deeply explored (Wang et al., 2010; Huang et al., 2015, 2018; Li et al., 2021). For example, Liu et al. (2017) found that during the 2014 APEC Summit, emission control mea-

asures dominated the reduction of PM_{2.5} concentrations when weather conditions were unfavorable, but the contributions of meteorology were often greater than those of emission controls when northwesterly winds prevailed. Ren et al. (2019) analyzed the characteristics of organic aerosols in PM_{2.5} during the 2015 Grand Military Parade and revealed a 40% reduction in lung cancer risk associated with inhaled PAHs due to the implementation of emission control measures. Xu et al. (2017) classified back trajectories obtained by the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPPLIT) and demonstrated that the lack of air mass transported from the south of Beijing was beneficial for maintaining low PM_{2.5} concentrations. Nonlocal emissions play an important role in the formation of severe haze through trans-regional transports of air pollutants, needing to implement strict emission reduction measures in cooperation with neighboring cities (Dang and Liao, 2019; Wu et al., 2021). It was reported that the airflow from Shandong, Hebei, and Inner Mongolia exerted tremendous impacts on Beijing’s haze, so in addition to controlling Beijing’s local emissions, factories in the surrounding provinces also need to be closed during the 2008 Olympic Games (Qiao et al., 2017). The Community Multiscale Air Quality (CMAQ) modeling system has been widely used to simulate air pollutants, identify sources of air pollution, and quantify the contributions of emission reductions and meteorology (Wu et al., 2018; Zhang et al., 2019; Xu and Chen, 2021). For example, Wang et al. (2017) calculated the contributions of local and nonlocal emission control measures using the Weather Research and Forecasting (WRF) model and CMAQ model, and found that the contributions of local emission reduction in Beijing to “APEC blue” (20.8%) and “Parade blue” (25.8%) were higher. The CMAQ equipped with Integrated Source Apportionment Model (ISAM) was applied by Dong et al. (2020) to explore the effects of regional transport, and their results showed that regional transports contributed 50.3% to Beijing’s PM_{2.5} concentrations in 2017. Chang et al. (2019) found that regional transports contributed differently in different periods, with contributions of 38%, 31%, 67% and 62% for January, March, July and October of 2014 in Beijing, respectively. They also calculated the contributions during the heavy pollution and clean days, confirming that the contributions of regional transports were stronger when PM_{2.5} concentrations were higher.

The 24th Winter Olympic Games with the spirit of “Faster, Higher, Stronger-Together” were held in Beijing from February 4 to 20, 2022. Since then, Beijing has become the first and only city in the world that has hosted both the Summer and Winter Olympic Games. In order to maintain China’s positive international image and fulfill the promises made during the Olympic bid, the Chinese government has taken a series of mandatory measures to protect air quality, such as temporary

controls of enterprises with heavy pollutions, high emissions, and relatively small economic impact, vehicle limits, and prohibition of fireworks and firecrackers. All competition venues equipped with low-carbon technologies were powered only by renewable energy sources such as wind, hydro and solar. The task of air quality assurance was successfully completed and Beijing experienced the best air quality in history, with $PM_{2.5}$ concentrations as low as single digits for several days. This was attributed to the combined effects of meteorological conditions and aggressive emission reduction measures.

Numerous studies in the past have shown that short-term emergency control measures imposed by the Chinese government have significantly improved air quality for major events held in Beijing in summer and autumn. The 2022 Winter Olympics was held in winter and coincided with the Chinese Lunar New Year, so determining the specific contributions of emission reductions and meteorology to successfully ensuring air quality has remarkable implications for the design of control policies for future mega events under the similar circumstances in Beijing. In this study, the WRF-CMAQ model was performed to distinguish the impacts of emission reduction measures at local, and regional scales adopted during the 2022 Winter Olympics. We assessed the impacts of meteorology on air quality by modeling and comparing meteorological conditions in 2021 and 2022. In addition, The CMAQ-ISAM and backward trajectories were used to analyze the contributions of regional transports to $PM_{2.5}$ in Beijing for the different pollution levels.

1. Experiment

1.1. Model configurations and emission inventory

The WRF-CMAQ model was used to simulate pollutant concentrations and study the influencing factors during the 2022 Winter Olympics. In this study, the model configurations were the same as those set in Yu et al. (2014). The physical schemes in the WRFv3.7 model included the asymmetric convective model (ACM2) for a planetary boundary layer scheme (Pleim, 2007), the Morrison double-moment cloud microphysics scheme (Morrison et al., 2009), the Kain-Fritsch (KF2) cumulus cloud parameterization, RRTMG longwave and shortwave radiation schemes, and the Pleim-Xiu (PX) land-surface scheme. The National Center for Environmental Prediction (NCEP) final analysis dataset with a spatial resolution of $1^\circ \times 1^\circ$ and a temporal resolution of 6 hr was used to provide meteorological initial and boundary conditions. The CMAQv5.0.2 with the carbon-bond chemical mechanism (CB05) and AERO6 aerosol module was applied in this study. The ISAM module was adopted to quantify the contributions of local and regional emissions to the surface concentrations of $PM_{2.5}$ in Beijing by continuously tracking species across a range of physical and chemical processes (Kwok et al., 2013). As shown in Fig. 1, the simulation domain covered most of China with the horizontal resolution of $36 \text{ km} \times 36 \text{ km}$ and 29 vertical layers. To study the influence of regional transport, Beijing, Tianjin, Hebei, Henan, Shanxi, Shandong, Liaoning, Inner Mongolia, and other region except those mentioned above in the domain were set as total 9 tagged regions. The anthro-

pogenic emissions were obtained from the Multi-resolution Emission Inventory for China (MEIC) (<http://www.meicmodel.org>) for 2016, which was developed by Tsinghua University and contained five emission sectors. Biogenic emissions from natural sources were calculated by the Biogenic Emissions Inventory System version 3.14 (BEISv3.14). The default initial and boundary chemical conditions were used and the first five days taken as the spin-up period were discarded to minimize the impact of initial chemical conditions (Wang et al., 2021b). The base case outputs of the day before the implementation of control measures was used as the initial and boundary conditions for the simulations in the scenario cases.

1.2. Observational data

The 2022 Winter Olympics venues include Beijing and Zhangjiakou, both of which were studied in this work. The 28 cities in Beijing-Tianjin-Hebei (BTH2+26 cities) are important cities on the air pollution transport channel in the North China Plain, and among the areas with the most serious air pollution in China. These cities include Beijing, Tianjin, Baoding, Cangzhou, Handan, Hengshui, Langfang, Shijiazhuang, Tangshan, Xingtai, Anyang, Hebi, Jiaozuo, Kaifeng, Puyang, Xinxiang, Zhengzhou, Changzhi, Jincheng, Taiyuan, Yangquan, Binzhou, Dezhou, Heze, Jinan, Jining, Liaocheng, and Zibo. BTH2+26 cities (except Beijing) near Beijing had a significant impact on Beijing's air quality (Zhang et al., 2021), so we compared the observed and simulated values in these cities to comprehensively evaluate the model performance. Hourly $PM_{2.5}$ concentrations observed in 29 cities were obtained from the China National Environmental Monitoring Centre (CNEMC) (<http://www.cnemc.cn/>). The meteorological measurements at every 3 hours were collected from the website (<http://www.meteomanz.com/>), including temperature (T), relative humidity (RH), air pressure (P), wind speed (WS) and wind direction (WD). The planetary boundary layer height (PBLH) values were derived from the fifth generation European Center for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA5) (<https://cds.climate.copernicus.eu/>).

1.3. Descriptions of simulations for emission control scenarios

In order to create a good air quality environment for the 2022 Winter Olympics, the Ministry of Ecology and Environment, together with 8 provinces (municipalities) including Beijing, Tianjin, Hebei, Henan, Shanxi, Shandong, Liaoning, and Inner Mongolia, took temporary control measures based on the forecast results (http://www.mee.gov.cn/ywdt/hjywnews/202203/t20220315_971533.shtml). The control period was from January 28 to February 20, 2022. During this period, the overall emissions of SO_2 , NO_x , PM_{10} , $PM_{2.5}$ and VOCs should be reduced by at least 50%, 40%, 45%, 45%, and 42%, respectively, to ensure that there was no moderate or above polluted weather (http://www.szpinglu.gov.cn/xxgk/zwgkml/xzgwml/xybxml/ggws/202112/t20211217_373528.html).

Six simulation cases for different emission control scenarios were designed to investigate contributions of meteorology

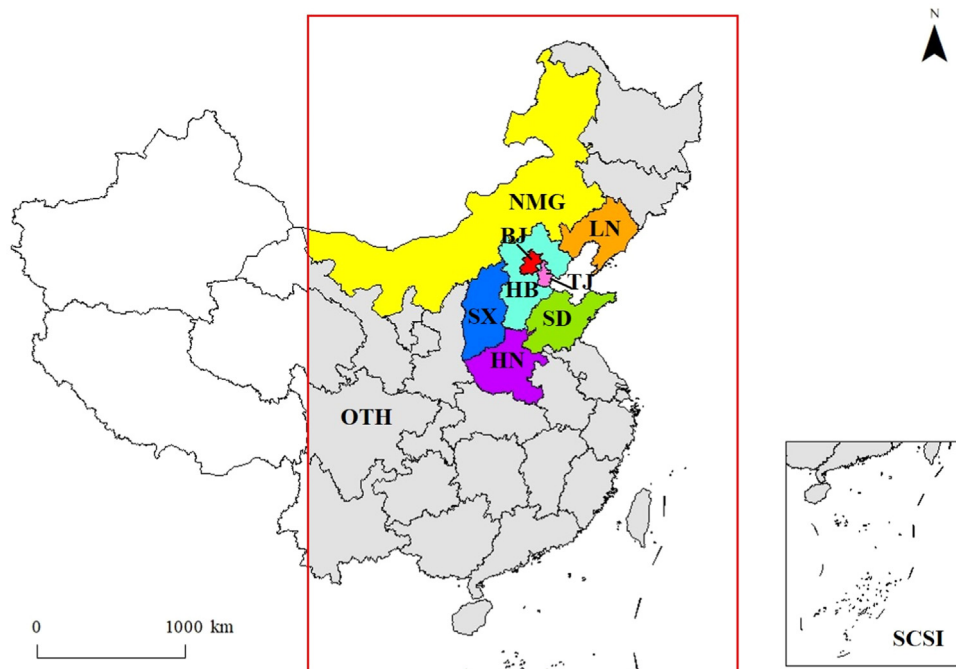


Fig. 1 – Map of the simulation domain (in the red frame) and the tracked source regions shown in different colors (BJ: Beijing; TJ: Tianjin; HB: Hebei; HN: Henan; SX: Shanxi; SD: Shandong; LN: Liaoning; NMG: Inner Mongolia; OTH: other regions in the domain; SCSI: South China Sea Islands).

and emission controls to the abatement of $PM_{2.5}$ concentrations during the 2022 Winter Olympics in Beijing, as listed in Table 1. B21 and B22 were the base cases from January 28 to February 20 in 2021 and 2022, respectively, under the corresponding meteorological conditions without emission reduction measures. According to different emission reduction regions and meteorological conditions, we designed four scenario cases, namely S1, S2, S3, and S4 (see Table 1). The differences between S1, S2, S3 and B22 can reflect the emission reduction contributions of different regions (Li et al., 2017). Comparing the $PM_{2.5}$ concentrations of S1 and S4, the influences by the meteorological conditions can be explained (Dong et al., 2020).

Note that the pollutant emissions for each sector in S1, S2 and S3 were reduced by the same percentage, which led to un-

certainties in the results of emission reduction contributions of local and surrounding regions due to the uncertainties of actual pollutant emission reductions in each sector. Therefore, 12 additional simulation cases were designed to reset the emission reduction percentages for each sector without changing the total reduction amounts of pollutants (Table 2), so as to analyse the impacts of uncertainties of emission reductions in different sectors on the results. The sources of pollutants in the emission inventory were divided into five sectors: agriculture, industry, power, residential and transportation, among which agriculture did not emit SO_2 , NO_x , $PM_{2.5}$, PM_{10} and VOCs. The emission reduction areas of S1.1, S1.2, S1.3, and S1.4 were the same as those of S1 by reducing the emissions of industry, power, residential, and transportation sectors in the largest percentages, while the reduction situ-

Table 1 – Descriptions of simulations for emission control scenarios.

Simulation cases	Meteorology	Provinces with emission controls	Emission reduction percentages (%)				
			SO_2	NO_x	$PM_{2.5}$	PM_{10}	VOCs
B22	2/4-2/20, 2022		0	0	0	0	0
B21	2/4-2/20, 2021		0	0	0	0	0
S1	2/4-2/20, 2022	Beijing, Tianjin, Hebei, Henan, Shanxi, Shandong, Liaoning, Inner Mongolia	-50	-40	-45	-45	-42
S2	2/4-2/20, 2022	Beijing	-50	-40	-45	-45	-42
S3	2/4-2/20, 2022	Tianjin, Hebei, Henan, Shanxi, Shandong, Liaoning, Inner Mongolia	-50	-40	-45	-45	-42
S4	2/4-2/20, 2021	Beijing, Tianjin, Hebei, Henan, Shanxi, Shandong, Liaoning, Inner Mongolia	-50	-40	-45	-45	-42

Table 2 – Descriptions of simulations for analyzing uncertainties by resetting the emission reduction percentages for each sector without changing the total reduction amounts of pollutants.

Simulation Cases	Sector	Emission reduction regions and percentages (%)									
		Beijing					Tianjin, Hebei, Henan, Shanxi, Shandong, Liaoning, Inner Mongolia				
		SO ₂	NO _x	PM _{2.5}	PM ₁₀	VOCs	SO ₂	NO _x	PM _{2.5}	PM ₁₀	VOCs
S1.1	IND	100%	93%	100%	100%	75%	100%	100%	100%	100%	82%
	POW	3%	0%	25%	25%	0%	3%	0%	13%	13%	0%
	RES	5%	0%	25%	25%	0%	5%	0%	14%	14%	0%
	TRA	5%	0%	25%	25%	0%	5%	0%	14%	14%	0%
S1.2	IND	48%	32%	44%	44%	42%	41%	26%	42%	42%	42%
	POW	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	RES	48%	34%	45%	45%	42%	42%	24%	40%	40%	42%
	TRA	48%	32%	43%	43%	41%	41%	26%	42%	42%	41%
S1.3	IND	20%	32%	0%	0%	28%	23%	37%	0%	0%	18%
	POW	20%	33%	0%	0%	28%	22%	35%	0%	0%	18%
	RES	100%	100%	69%	69%	100%	100%	100%	86%	86%	100%
	TRA	18%	33%	0%	0%	28%	22%	35%	0%	0%	18%
S1.4	IND	44%	9%	42%	42%	24%	49%	10%	43%	43%	29%
	POW	44%	9%	41%	41%	24%	49%	9%	42%	42%	29%
	RES	44%	9%	41%	41%	23%	49%	9%	43%	43%	29%
	TRA	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
S2.1	IND	100%	93%	100%	100%	75%	0%	0%	0%	0%	0%
	POW	3%	0%	25%	25%	0%	0%	0%	0%	0%	0%
	RES	5%	0%	25%	25%	0%	0%	0%	0%	0%	0%
	TRA	5%	0%	25%	25%	0%	0%	0%	0%	0%	0%
S2.2	IND	48%	32%	44%	44%	42%	0%	0%	0%	0%	0%
	POW	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%
	RES	48%	34%	45%	45%	42%	0%	0%	0%	0%	0%
	TRA	48%	32%	43%	43%	41%	0%	0%	0%	0%	0%
S2.3	IND	20%	32%	0%	0%	28%	0%	0%	0%	0%	0%
	POW	20%	33%	0%	0%	28%	0%	0%	0%	0%	0%
	RES	100%	100%	69%	69%	100%	0%	0%	0%	0%	0%
	TRA	18%	33%	0%	0%	28%	0%	0%	0%	0%	0%
S2.4	IND	44%	9%	42%	42%	24%	0%	0%	0%	0%	0%
	POW	44%	9%	41%	41%	24%	0%	0%	0%	0%	0%
	RES	44%	9%	41%	41%	23%	0%	0%	0%	0%	0%
	TRA	100%	100%	100%	100%	100%	0%	0%	0%	0%	0%
S3.1	IND	0%	0%	0%	0%	0%	100%	100%	100%	100%	82%
	POW	0%	0%	0%	0%	0%	3%	0%	13%	13%	0%
	RES	0%	0%	0%	0%	0%	5%	0%	14%	14%	0%
	TRA	0%	0%	0%	0%	0%	5%	0%	14%	14%	0%
S3.2	IND	0%	0%	0%	0%	0%	41%	26%	42%	42%	42%
	POW	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%
	RES	0%	0%	0%	0%	0%	42%	24%	40%	40%	42%
	TRA	0%	0%	0%	0%	0%	41%	26%	42%	42%	41%
S3.3	IND	0%	0%	0%	0%	0%	23%	37%	0%	0%	18%
	POW	0%	0%	0%	0%	0%	22%	35%	0%	0%	18%
	RES	0%	0%	0%	0%	0%	100%	100%	86%	86%	100%
	TRA	0%	0%	0%	0%	0%	22%	35%	0%	0%	18%
S3.4	IND	0%	0%	0%	0%	0%	49%	10%	43%	43%	29%
	POW	0%	0%	0%	0%	0%	49%	9%	42%	42%	29%
	RES	0%	0%	0%	0%	0%	49%	9%	43%	43%	29%
	TRA	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%

IND: industry; POW: power plants; RES: residential sector; TRA: transportation.

ations of the remaining sectors were similar. S2.1, S2.2, S2.3, and S2.4 set the same emission reduction regions as S2 with the same emission reduction percentages as S1.1, S1.2, S1.3, and S1.4, respectively. S3.1, S3.2, S3.3, and S3.4 set the same emission reduction regions as S3 with the same emission reduction percentages as S1.1, S1.2, S1.3, and S1.4, respectively.

1.4. Backward trajectory

The HYSPLIT model developed by the National Oceanic and Atmospheric Administration (NOAA) was used to calculate backward trajectories for this study period. We employed a concentration weighted trajectory (CWT) method to identify

the transport pathways of regional-scale air masses and assess the contributions of source sites to the pollution in the receptor regions (Chen et al., 2020). A high CWT value implies a large potential contribution of the grid cell over which the air-flow passes to the pollution in the receptor region (Yan et al., 2015). In this study, 48-h backward trajectories were calculated for eight times a day (00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00, UTC time) at an arrival height of 100 m above the ground level.

2. Results and discussion

2.1. Evaluation of the model performances

Since air quality assurance emergency drills were conducted in China before and after the 2022 Winter Olympics to improve the ability to cope with potential heavy pollution, this study selected the 2022 Winter Olympics period for model performance evaluation. Fig. 2 shows time series of the simulated and observed hourly PM_{2.5} concentrations from February 4 to 20, 2022, in BTH2+26 cities and Zhangjiakou. The model markedly overestimated the actual observations in the B22 case without considering the implementation of stringent air quality control measures. For the S1 case, the model simulations showed better agreements with observations for most cities. We used statistical metrics to evaluate the model performance, including the mean bias (MB), the mean error (ME), the normalized mean bias (NMB), the normalized mean error (NME), and the correlation coefficient (R) (Yu et al., 2006). Table 3 summarizes the simulated PM_{2.5} concentrations in the B22 and S1 cases versus hourly observations for these cities. Compared with the B22 case, the S1 case exhibited better model performance in Beijing, with the NMB, NME, and R values of -19.8%, 39.2% and 0.70, respectively. On the other hand, PM_{2.5} concentrations in Zhangjiakou during the 2022 Winter Olympics were very low with the mean concentration of 18.8 µg/m³ and the model also did not predict any pollution events for Zhangjiakou (see Fig. 2b). The mean PM_{2.5} concentration under the B22 scenario was 17.5 µg/m³, closer to the observation, than that under the S1 scenario as shown in Table 3. Different cities had different predictions of pollution levels, so the actual intensities of emission control measures differed. Model performance errors are mainly related to the uncertainty of emission inventory, inappropriate setting of emission reduction percentages, and systematic errors of the CMAQ model itself (Jia et al., 2017; Zheng et al., 2021; Yu et al., 2014). Overall, the model reproduced the variations in PM_{2.5} concentrations generally well and could be used to further analyze the impact of emission reductions and meteorological conditions.

2.2. Contributions of meteorological conditions

Fig. 3 compares observed meteorological parameters in 2021 and 2022 in terms of T, RH, P, WS, WD, and PBLH. During the 2022 Winter Olympics, there were frequent cold air activities in Beijing. Especially during and after the opening ceremony, Beijing continued to be affected by the cold air from the north,

being beneficial to reduce pollution (Meng et al., 2019). Compared to the same period in 2021 in Beijing, P (from 1021 hPa to 1030 hPa) and WS (from 1.9 m/s to 2.1 m/s) in 2022 were relatively higher, while T (from 3°C, to -2°C,) and RH (from 42% to 39%) were relatively lower, indicating that the atmospheric diffusion conditions were relatively good, being conducive to the decreases of pollutant concentrations (Bei et al., 2020). The chemical reaction rates, volatilization of substances such as ammonium nitrate, and photolysis related to the generation of haze pollution are largely dependent on T (Gao et al., 2016). The higher RH not only enhances the hygroscopic growth of particles, but also promotes the secondary transformation of gaseous precursors and accelerates the formation of secondary species such as nitrate (Sun et al., 2006; Zhang et al., 2015; Li et al., 2019). Thus, the relatively lower T and RH in Beijing during the 2022 Winter Olympics were unfavorable for the aerosol productions. The PBLH is negatively correlated with the surface PM_{2.5} concentrations, suggesting that lower PBLH accompanying with weaker turbulent diffusion is favorable for formation of haze (Wang et al., 2015). Therefore, the meteorological conditions in Beijing in 2022 played a crucial role in maintaining good air quality for the 2022 Winter Olympics. Compared to the same period in 2021 in Zhangjiakou, P (from 1023 hPa to 1032 hPa), WS (from 2.7 m/s to 3.0 m/s) and RH (from 34% to 47%) in 2022 were relatively higher, and T (from -0.7°C to -8.6°C) was relatively lower. The negative effect of high RH may counteract the positive effect of low T and high WS, resulting in little meteorological impact on Zhangjiakou for the whole period.

The difference in the simulated results between B22 and B21 cases was attributed to the effect of meteorological conditions, as we used the same emission inventory for both cases. To identify the contributions of meteorological conditions to the Olympic blue sky under the implementation of emission reduction measures during the 2022 Winter Olympics, we designed two sensitivity cases (S1 and S4) with the same emissions but under the two different meteorological conditions, and compared these two simulated results by following Xing et al. (2011), Wang et al. (2020), and Chen et al. (2021). Fig. 4f illustrates that compared to the meteorological conditions in 2021, meteorological conditions in 2022 decreased PM_{2.5} concentrations in Beijing, but produced large increases in PM_{2.5} concentrations in most other regions such as Henan, Shandong, and Shanxi. This study revealed that the meteorological contributions to the reductions of PM_{2.5} concentrations in Beijing in 2022 with and without emission control measures were 6.9 and 11.8 µg/m³, respectively, which were between the results of Cheng et al. (2019) (with concentration of 4.4 µg/m³) and Zhang et al. (2021) (with concentration of 12.3 µg/m³). For Zhangjiakou, the meteorological contributions were almost negligible, increasing PM_{2.5} concentrations by only 0.8 and 1.3 µg/m³ for the cases with and without emission control measures, respectively, because of very low PM_{2.5} concentrations there. This was consistent with the above analysis results of meteorological observation data in Beijing and Zhangjiakou. The changes in Figs. 4c and 4f indicate that meteorology played different roles in PM_{2.5} concentrations under the different emission conditions. When pollutant emissions were reduced, the changes in PM_{2.5} concentrations caused by changes in meteorological conditions were

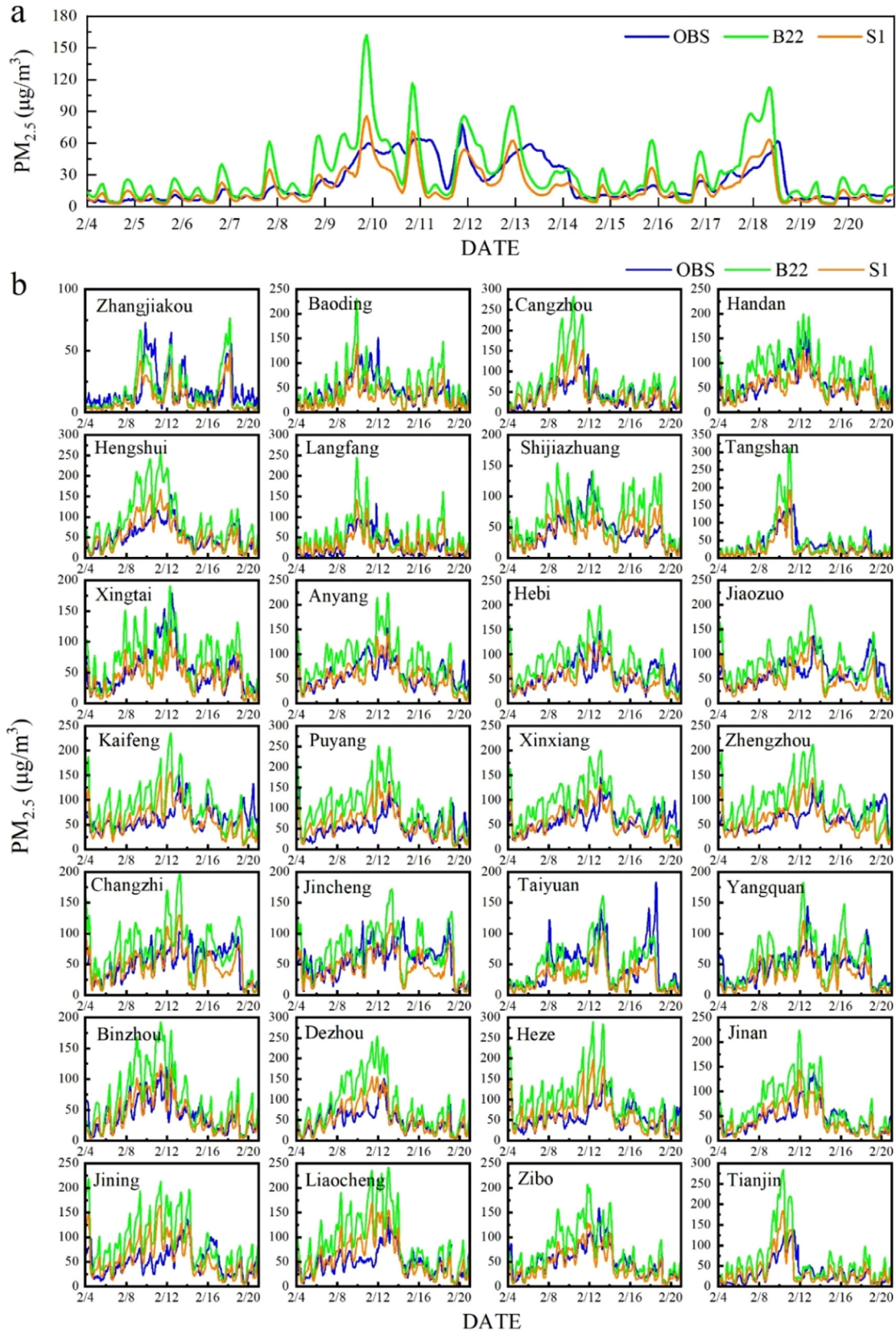


Fig. 2 – The comparisons of hourly $PM_{2.5}$ concentrations for observations and model simulations for B22 and S1 cases during the period of February 4 to 20, 2022, in (a) Beijing and (b) other 28 cities.

Table 3 – Model evaluation statistics for PM_{2.5} concentrations in 29 cities for the period from February 4 to 20, 2022, for the B22 and S1 simulation cases.

City	Cases	OBS	SIM	MB	ME	NMB	NME	R
Beijing	B22	23.1	31.6	8.4	15.4	36.4%	66.7%	0.67
	S1	23.1	18.6	-4.6	9.1	-19.8%	39.2%	0.70
Zhangjiakou	B22	18.8	17.5	-1.3	9.1	-6.8%	48.2%	0.66
	S1	18.8	11.2	-7.6	10.0	-40.4%	53.1%	0.68
Baoding	B22	43.9	51.5	7.6	25.1	17.3%	57.2%	0.54
	S1	43.9	31.6	-12.4	19.4	-28.1%	44.0%	0.54
Cangzhou	B22	40.8	69.4	28.6	33.6	70.0%	82.3%	0.71
	S1	40.8	43.9	3.1	16.5	7.5%	40.3%	0.71
Handan	B22	60.7	80.6	19.9	29.4	32.8%	48.3%	0.64
	S1	60.7	50.1	-10.6	19.6	-17.4%	32.2%	0.68
Hengshui	B22	54.0	88.3	34.3	40.0	63.5%	74.1%	0.74
	S1	54.0	55.2	1.2	18.6	2.2%	34.5%	0.75
Langfang	B22	30.1	51.7	21.7	28.7	72.1%	95.6%	0.63
	S1	30.1	32.4	2.3	16.9	7.7%	56.3%	0.63
Shijiazhuang	B22	45.6	65.1	19.5	26.8	42.6%	58.8%	0.53
	S1	45.6	40.6	-5.0	17.4	-11.0%	38.1%	0.57
Tangshan	B22	38.3	44.8	6.5	20.8	17.1%	54.3%	0.77
	S1	38.3	27.6	-10.7	15.7	-27.9%	41.0%	0.77
Xingtai	B22	55.1	70.6	15.4	30.5	28.0%	55.3%	0.54
	S1	55.1	44.1	-11.1	21.5	-20.1%	38.9%	0.59
Anyang	B22	59.4	85.0	25.6	33.4	43.1%	56.3%	0.60
	S1	59.4	53.5	-5.9	17.9	-10.0%	30.1%	0.63
Hebi	B22	60.5	80.5	19.9	30.0	32.9%	49.5%	0.58
	S1	60.5	51.2	-9.3	18.8	-15.4%	31.0%	0.61
Jiaozuo	B22	64.6	78.4	13.7	31.0	21.2%	48.0%	0.41
	S1	64.6	50.8	-13.8	24.9	-21.4%	38.6%	0.44
Kaifeng	B22	62.6	88.3	25.7	37.4	41.0%	59.8%	0.35
	S1	62.6	58.1	-4.5	24.1	-7.2%	38.4%	0.34
Puyang	B22	55.7	98.2	42.4	48.0	76.2%	86.1%	0.58
	S1	55.7	62.5	6.8	22.6	12.2%	40.6%	0.59
Xinxiang	B22	60.1	86.5	26.5	34.4	44.1%	57.3%	0.52
	S1	60.1	55.4	-4.7	20.1	-7.7%	33.4%	0.55
Zhengzhou	B22	63.2	93.8	30.6	40.8	48.4%	64.6%	0.30
	S1	63.2	60.9	-2.3	24.2	-3.7%	38.3%	0.33
Changzhi	B22	53.5	72.3	18.8	30.6	35.1%	57.2%	0.51
	S1	53.5	46.3	-7.2	19.3	-13.4%	36.1%	0.53
Jincheng	B22	56.8	72.0	15.2	27.6	26.7%	48.6%	0.44
	S1	56.8	46.5	-10.3	20.4	-18.1%	35.9%	0.47
Taiyuan	B22	47.5	45.3	-2.3	21.3	-4.8%	44.9%	0.61
	S1	47.5	29.3	-18.2	22.5	-38.4%	47.3%	0.65
Yangquan	B22	46.3	53.9	7.6	22.7	16.4%	49.1%	0.58
	S1	46.3	34.5	-11.8	19.3	-25.5%	41.7%	0.60
Binzhou	B22	42.8	66.4	23.6	28.3	55.1%	66.1%	0.78
	S1	42.8	42.2	-0.6	13.6	-1.4%	31.9%	0.79
Dezhou	B22	49.7	86.5	36.9	39.2	74.2%	79.0%	0.76
	S1	49.7	54.4	4.7	17.5	9.5%	35.2%	0.77
Heze	B22	58.2	96.5	38.2	46.1	65.6%	79.2%	0.57
	S1	58.2	62.7	4.5	25.5	7.7%	43.7%	0.56
Jinan	B22	46.0	67.7	21.7	26.8	47.3%	58.4%	0.77
	S1	46.0	43.4	-2.6	15.3	-5.6%	33.2%	0.76
Jining	B22	50.2	87.2	37.0	43.3	73.8%	86.3%	0.61
	S1	50.2	57.5	7.3	24.2	14.6%	48.3%	0.57
Liaocheng	B22	48.5	89.7	41.1	43.7	84.7%	90.1%	0.75
	S1	48.5	57.6	9.0	19.8	18.6%	40.7%	0.74
Zibo	B22	51.4	69.2	17.9	24.3	34.8%	47.3%	0.79
	S1	51.4	43.7	-7.7	14.8	-14.9%	28.8%	0.80
Tianjin	B22	34.5	58.3	23.8	31.2	69.1%	90.4%	0.76
	S1	34.5	36.8	2.3	15.6	6.6%	45.2%	0.76

OBS: average observation concentrations; SIM: average concentrations of simulations; MB: mean bias; ME: mean error; NMB: normalized mean bias; NME: normalized mean error; R: correlation coefficient. The units for OBS, SIM, MB, and ME are $\mu\text{g}/\text{m}^3$.

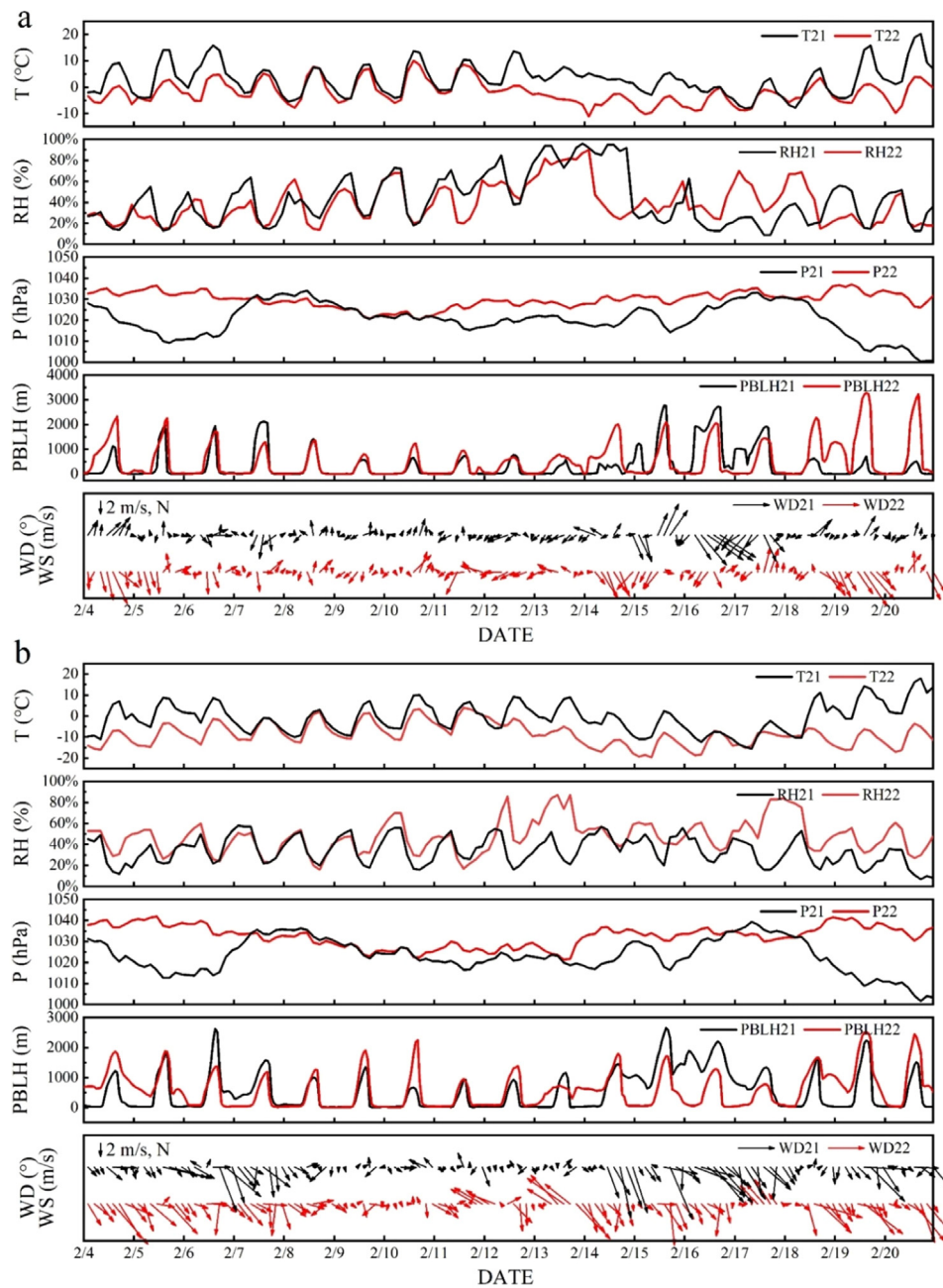


Fig. 3 – Time series of observed meteorological parameters including temperature (T), relative humidity (RH), air pressure (P), planetary boundary layer height (PBLH), wind speed (WS) and wind direction (WD) in (a) Beijing and (b) Zhangjiakou for the periods from February 4 to 20, 2021 (21) and 2022 (22).

also reduced accordingly. Emission reductions were effective in offsetting part of the negative effects of adverse meteorological conditions. In the daily control of air quality, meteorological conditions should be taken into consideration, and emission control measures should be formulated in advance according to the meteorological conditions.

2.3. Effects of various emission control schemes

The cold winter requiring central heating was the main period of air pollution events in the North China Plain (Cheng et al.,

2017). Therefore, it was necessary to take emission control policies for mega events to directly reduce the emissions of primary $PM_{2.5}$, while decreasing the emissions of precursors to reduce the amounts of secondary $PM_{2.5}$ generated by the chemical conversions (Shang et al., 2022). According to the analyses of observational data from February 4 to 20, 2022, the average value of $PM_{2.5}$ concentrations in Beijing was $23 \mu\text{g}/\text{m}^3$ with the highest value of $78 \mu\text{g}/\text{m}^3$, and the lowest value of $4 \mu\text{g}/\text{m}^3$. The average value of $PM_{2.5}$ concentrations in Zhangjiakou was $19 \mu\text{g}/\text{m}^3$ with the highest value of $73 \mu\text{g}/\text{m}^3$, and the lowest value of $3 \mu\text{g}/\text{m}^3$. The daily air quality index (AQI)

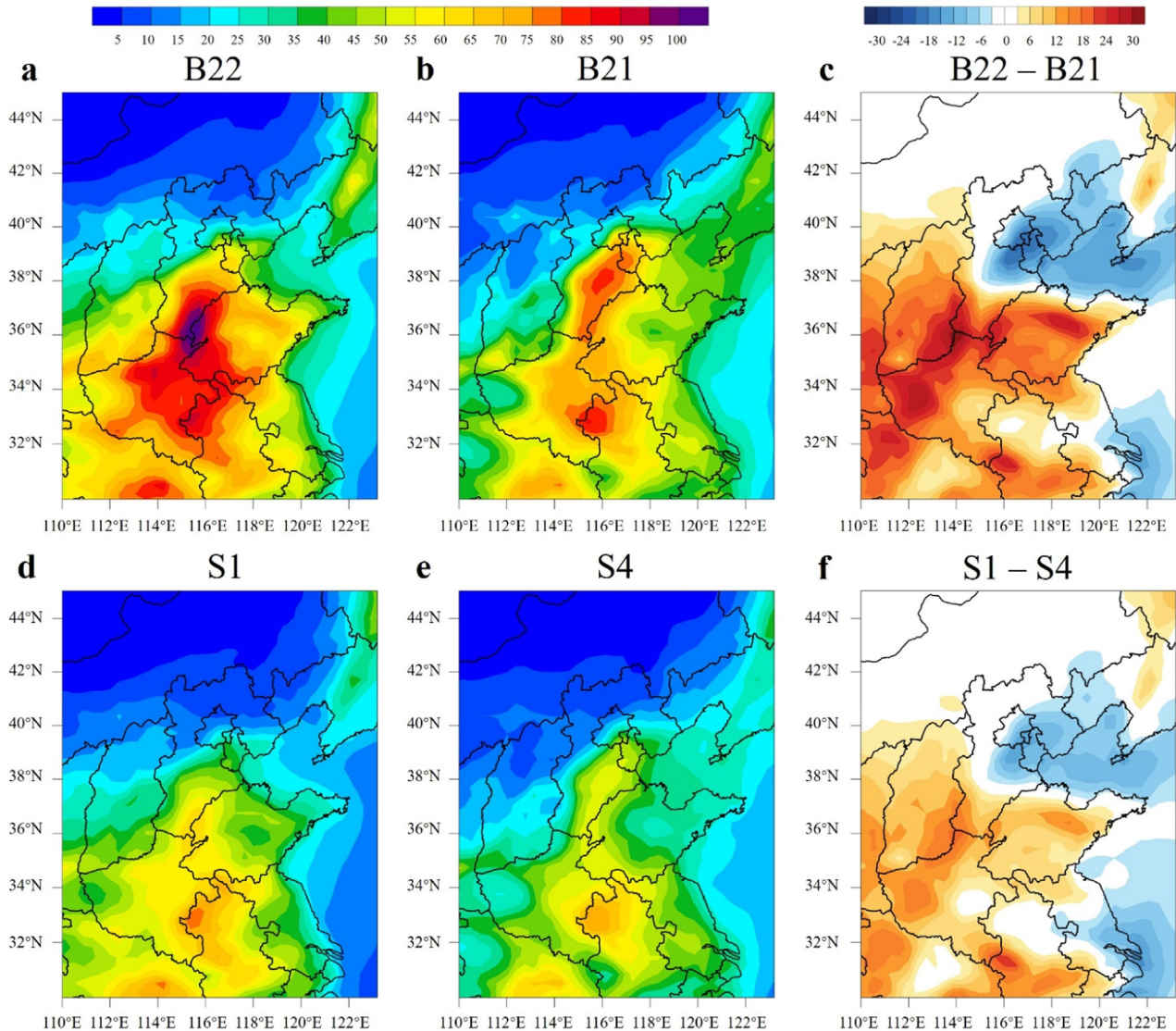


Fig. 4 – Spatial distributions of mean $PM_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) for different simulations: (a) B22 case, (b) B21 case, (c) The differences between B22 and B21 cases, (d) S1 case, (e) S4 case, (f) The differences between S1 and S4 cases. The simulation periods were from February 4 to 20, 2022.

values were within the range of excellent and good, indicating that the air quality in both cities reached the predetermined standard, which was inseparable from the effects of emission reduction measures. If no control measures were taken, light pollution events might occur in Beijing from February 9 to February 13 as predicted by the model for the base case B22.

Fig. 5 shows the spatial distributions of the decreases of mean $PM_{2.5}$ concentrations calculated by the difference between model simulations with and without emission reduction measures. During the 2022 Winter Olympics, the implementations of emission control measures in all 8 provinces (municipalities) resulted in a decrease of $13.0 \mu\text{g}/\text{m}^3$ (-41.2%) in average $PM_{2.5}$ concentrations in Beijing. The emission reductions strongly mitigated the upward trends of $PM_{2.5}$ and played a prominent role in reducing the peak $PM_{2.5}$ concentrations. For example, the peak $PM_{2.5}$ concentrations in Beijing

were decreased from 113 to $63 \mu\text{g}/\text{m}^3$ on February 18 as predicted by the model. Although each city made great efforts to reduce emissions, the absolute values of $PM_{2.5}$ decreases varied, indicating that there were spatial differences in the emission reduction effects (Fig. 5a). Significant reductions in the absolute values of $PM_{2.5}$ were observed in southern Hebei, northern Henan and western Shandong. These cities located in the southwest to northeast direction along the Taihang Mountains were important industrial cities in the North China Plain, where heavy pollution events occurred frequently (Sun et al., 2015). There was a clear consistency between the emission reduction effects and $PM_{2.5}$ concentration levels in the controlled regions, demonstrating that the emission reduction effects were influenced by the amount of pollutants emitted locally. In contrast to absolute contributions, the relative contributions were similar in all controlled regions except for north-

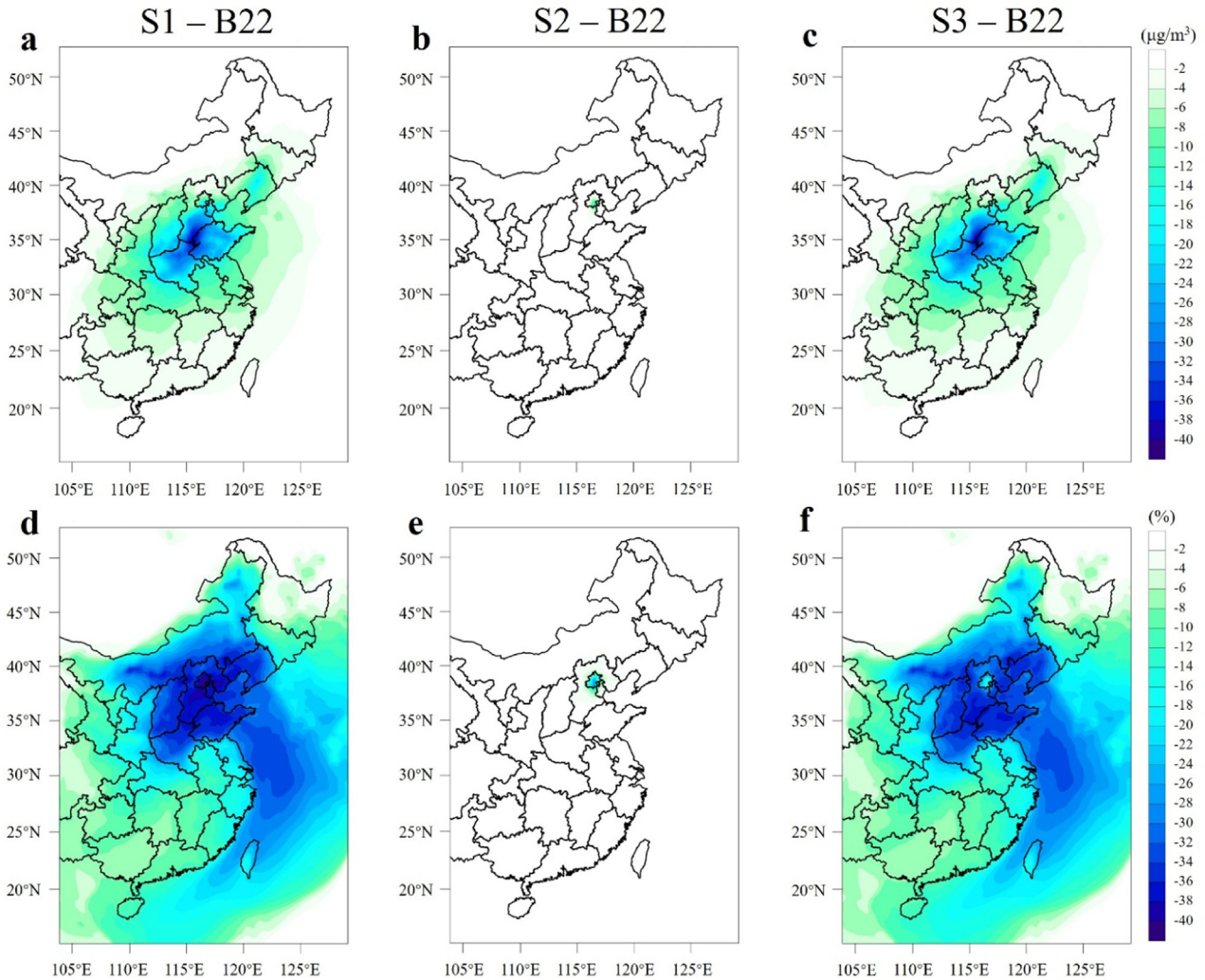


Fig. 5 – Spatial distributions of differences in mean $PM_{2.5}$ concentrations attributed to various emission control measures from February 4 to 20, 2022. The first and second rows are absolute values and relative percentages, respectively. (a, d) The differences between S1 and B22 cases, (b, e) the differences between S2 and B22 cases, (c, f) the differences between S3 and B22 cases.

ern Inner Mongolia with more than 30% (Fig. 5d). The high decrease percentages of $PM_{2.5}$ concentrations in the controlled regions reflected the notable effects of strict emission reduction measures during the 2022 Winter Olympics. Emission reductions not only affected local air pollutants, but also had a positive impact on the surrounding uncontrolled areas. As shown in Fig. 5, the $PM_{2.5}$ concentrations in Shaanxi, Hubei, Anhui and Jiangsu provinces decreased by 5 to 15 $\mu\text{g}/\text{m}^3$. This was related to regional transports, which moved the pollutants emitted by one city to other cities, resulting in regional pollution. The cities in BTH and its neighboring cities were closely connected because of regional transports among them, and pollution levels were affected by the entire regional transports (Wang et al., 2014).

Accurate quantification of local and nonlocal contributions of emission reductions to $PM_{2.5}$ is critical for establishing effective and economical control policies to improve air quality during the severe haze episodes. Two sensitivity cases, namely

S2 and S3 cases, were designed to further figure out the separate contributions of emission reduction measures implemented in Beijing and its surrounding controlled regions. The difference of $PM_{2.5}$ concentrations between S2 and B22 cases represented the contribution of local emission reduction measures, while those between S3 and B22 cases denoted the contribution of nonlocal emission reduction measures. If only Beijing took emission control measures, the average $PM_{2.5}$ concentrations in Beijing would be decreased by 7.2 $\mu\text{g}/\text{m}^3$ (Fig. 5b) only, accounting for 22.8% of total reductions (Fig. 5e). Except for Langfang and Baoding, which are very close to Beijing, other cities were basically not affected in this case. On the other hand, when emission control measures were taken only in the surrounding regions without Beijing, pollutions in these regions were significantly reduced, and the air quality in Beijing was positively improved. Beijing's $PM_{2.5}$ concentrations would be decreased by 5.8 $\mu\text{g}/\text{m}^3$ (Fig. 5c), accounting for 18.3% of total reductions (Fig. 5f) in this case. The result

shows that the contributions of Beijing's local emission reductions to low $PM_{2.5}$ concentrations in Beijing during the 2022 Winter Olympics are slightly higher than the contributions of nonlocal emission reductions. This is similar to the results of Guo et al. (2016), who also found a larger contribution of local emission reductions in Beijing during the 2014 APEC.

When different emission reduction percentages were adopted in different sectors, the simulated $PM_{2.5}$ concentrations in Beijing were different. In S1.1, S1.2, S1.3, and S1.4, the average $PM_{2.5}$ concentrations in Beijing decreased by 9.3, 12.8, 16.8, and 13.5 $\mu\text{g}/\text{m}^3$, respectively. Compared with the results obtained by adopting the same reduction percentages for all sectors (S1), the contributions of anthropogenic emission reduction scenarios set in S1.1, S1.2, S1.3, and S1.4 were enhanced by -3.7, -0.2, 3.9, and 0.5 $\mu\text{g}/\text{m}^3$, respectively. S1.1 mainly controlled pollutants in the industrial sector, and contributed less to the reduction of $PM_{2.5}$ concentrations than the other three cases. S1.3 mainly controlled pollutants in the residential sector, and its contribution to the reduction of $PM_{2.5}$ concentrations was the largest among all cases, indicating that the control of residential pollutants played an important role in the mitigation of $PM_{2.5}$ pollutions. Although S1.2 and S1.4 did not consider the pollutant emissions from the power and transportation sectors, the simulation results obtained were very close to those of S1 because the emissions of these two sectors were relatively low and the emission reduction

percentages set by other sectors were large. In fact, during the 2022 Winter Olympics, Beijing and its surrounding regions did not target a single sector for pollutant controls only, so sector factors had little impact on the relevant results. The comparisons of S2 with S2.1 ~ S2.4, and S3 with S3.1 ~ S3.4 indicate that the influence of different emission reduction percentages for each sector on the local and nonlocal control contributions ranged from -2.0 to 1.7 $\mu\text{g}/\text{m}^3$ and -1.4 to 2.2 $\mu\text{g}/\text{m}^3$, respectively. The results showed that the local emission reduction had a greater contribution, being consistent with the above conclusions.

2.4. Local emission and regional transport effects under the different pollution levels

We divided the 2022 Winter Olympics into five study periods based on the predicted $PM_{2.5}$ concentrations: February 4-8 (P1), February 9-13 (P2), February 14-16 (P3), February 17-18 (P4), and February 19-20 (P5). P1, P3, and P5 were the cleaning periods with $PM_{2.5}$ concentrations maintained at very low levels, while P2 and P4 were the potential pollution periods, containing the accumulation processes of $PM_{2.5}$. The CWT values illustrating movement directions of air masses and potential source contributions on the basis of observed $PM_{2.5}$ are shown in Fig. 6. During the whole period of the 2022 Winter Olympics, the regional transport pathways mainly came from the northwest,

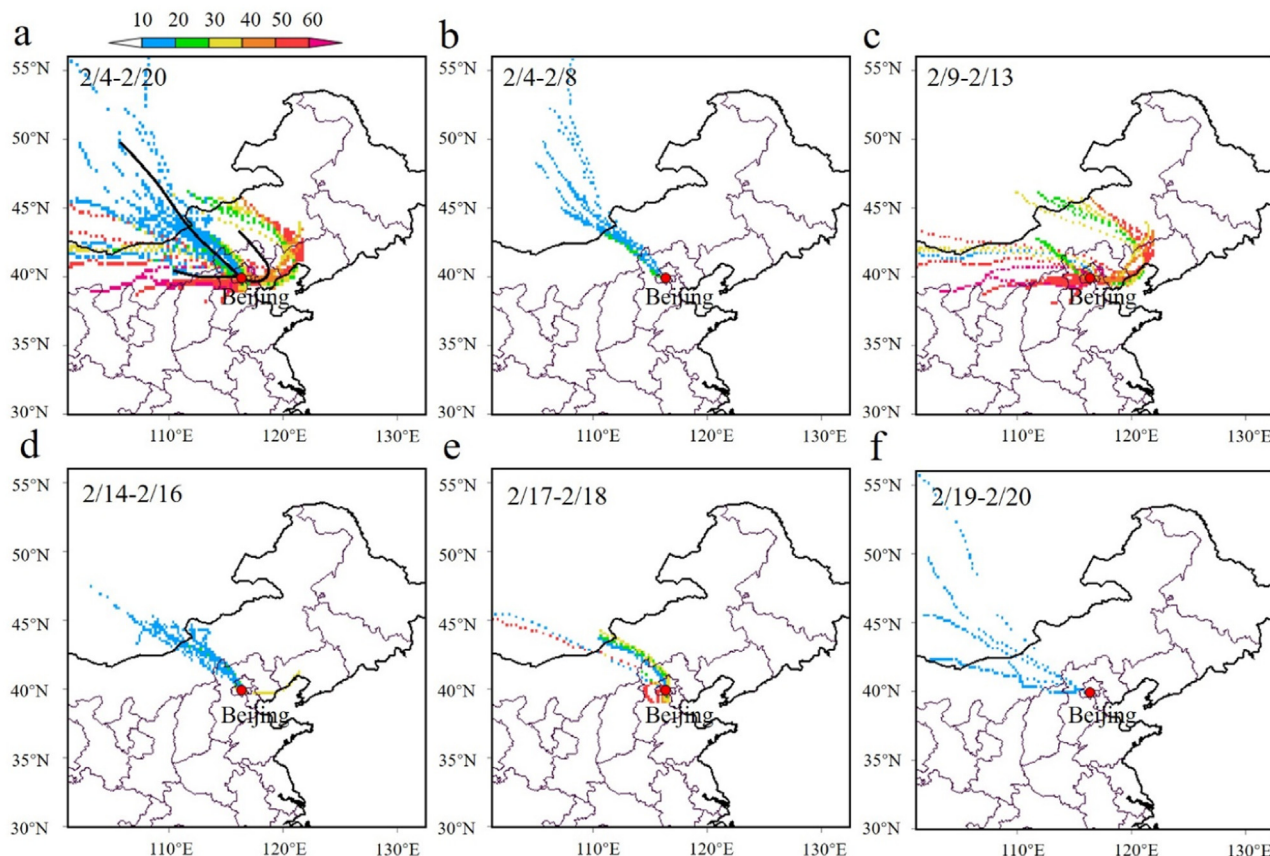


Fig. 6 – The CWT maps for observed $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$) for Beijing for the periods of (a) 4-20 February, (b) 4-8 February, (c) 9-13 February, (d) 14-16 February, (e) 17-18 February, and (f) 19-20 February. The red dot represents Beijing.

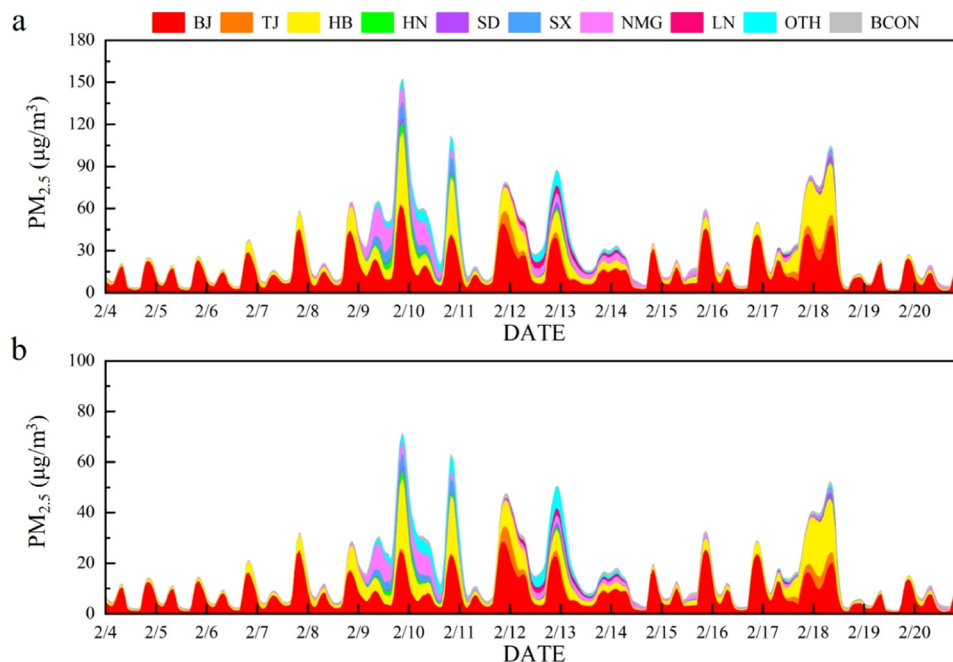


Fig. 7 – Time series of the contributions from local, different areas and boundary conditions (BCON) to $PM_{2.5}$ concentrations in Beijing in the (a) B22 and (b) S1 cases.

east-northeast, and west-southwest directions. Among them, Beijing was largely influenced by clean air masses originating from Inner Mongolia in the three cleaning periods. During the period of P2, some air masses arriving in Beijing from the east-northeast passed through the areas such as Tangshan and Langfang, while other air masses arriving in Beijing from the west-southwest passed through the areas such as Datong and Baoding, all of which were heavily polluted cities in the northern region. The topography of Beijing is high in the northwest and low in the southeast, with mountains surrounding it in the west, north and northeast (Deng et al., 2022). Therefore, air pollutants transported from the south and east were not conducive to diffusion, tending to increase Beijing's pollutant concentrations. The back trajectories of P4 show that the air masses passed through the polluted cities such as Langfang, Baoding, and Datong, and the contributions of these cities to Beijing's pollution were greater than those of Inner Mongolia.

We quantified the contributions of various sources to $PM_{2.5}$ in Beijing using the CMAQ-ISAM model, and the hourly contributions of 9 regions and boundary conditions in the model simulations for B22 and S1 cases are presented in Fig. 7. In the absence of emission reduction measures, due to the large amount of pollutants emitted by each region, the contribution values of each source to Beijing's $PM_{2.5}$ were large, but the contribution percentages of each source were similar in the case with and without emission reduction measures (Table 4). The simulations of S1 case reveal that, on average, local sources were the dominant contributor (47.7%) to $PM_{2.5}$ in Beijing during the 2022 Winter Olympics. Among nonlocal sources, the top four contributors were Hebei (24.4%), Inner Mongolia (8.5%), other regions (5.3%), and boundary conditions (5.0%). During the cleaning periods (P1, P3, and P5), Beijing's $PM_{2.5}$ concentrations were controlled by local emissions,

with contribution percentages ranging from 67.3% to 69.9%. The regional contributions mainly came from Hebei (14.2% to 20.5%) and Inner Mongolia (3.5% to 7.1%), which were consistent with the main areas as shown in the CWT values. During the period of P2, the local contribution values increased, but the local contribution percentages (35.3%) decreased significantly due to the effects of regional transports. Compared with the cleaning periods, the contribution percentages of the surrounding areas all increased, which played a significant role in the increase of $PM_{2.5}$ concentrations in Beijing for this period. During the period of P4, the local sources contributed 39.6%, and nonlocal sources contributed 60.4%. Different from the regional contributions in the P2 period, in which air masses came from various regions, the regional contributions in this period mainly came from Hebei (39.8%) and Tianjin (8.4%). In general, the influences of regional transports were great in the potential pollution periods, and the main source area was determined mainly by the wind directions at the regional scale.

For the entire period of the 2022 Winter Olympics, the impact of emission reduction measures was $-13.0 \mu\text{g}/\text{m}^3$ of $PM_{2.5}$ in Beijing with the different contributions in different periods as shown in Fig. 8. Local emission reductions in Beijing were continuously meaningful for decreasing $PM_{2.5}$ concentrations with decreases of -5.9 , -9.0 , -6.2 , -10.6 , and $-4.2 \mu\text{g}/\text{m}^3$ for the periods of P1, P2, P3, P4, and P5, respectively, while they were -1.8 , -11.8 , -2.8 , -9.5 , and $-1.1 \mu\text{g}/\text{m}^3$, respectively, for the implementation of emission reductions in the surrounding regions of Beijing only (i.e., the nonlocal emission reductions). It was found that during the cleaning periods, the local emission reduction contributions dominated the $PM_{2.5}$ decreases, much larger than the nonlocal emission reduction contributions, while during the potential pollution periods, both local and nonlocal emission reductions played an equally impor-

Table 4 – Average contributions (the units are $\mu\text{g}/\text{m}^3$) from various sources to $\text{PM}_{2.5}$ in Beijing during the 2022 Winter Olympics for the B22 and S1 cases during the different periods (P1, P2, P3, P4 and P5). The values in parentheses are contribution percentages (the units are %).

Region	BJ	TJ	HB	HN	SD	SX	NMG	LN	OTH	BCON
B22										
P1	11.9 (71.5)	0.0 (0.2)	3.4 (20.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.2)	0.7 (4.3)	0.0 (0.0)	0.0 (0.0)	0.6 (3.5)
P2	18.1 (37.1)	1.5 (3.1)	11.4 (23.4)	1.2 (2.5)	0.5 (1.1)	2.7 (5.5)	7.0 (14.3)	1.3 (2.7)	3.5 (7.2)	1.4 (2.9)
P3	14.0 (66.6)	0.1 (0.5)	3.4 (16.2)	0.0 (0.0)	0.0 (0.0)	0.1 (0.7)	2.0 (9.4)	0.2 (1.0)	0.2 (0.9)	1.0 (4.6)
P4	19.2 (45.1)	3.2 (7.6)	15.6 (36.5)	0.2 (0.4)	0.7 (1.6)	0.3 (0.8)	1.4 (3.2)	0.4 (0.9)	0.4 (1.0)	1.2 (2.8)
P5	8.6 (73.1)	0.0 (0.0)	1.7 (14.3)	0.0 (0.0)	0.0 (0.0)	0.1 (0.5)	0.7 (6.1)	0.0 (0.0)	0.0 (0.0)	0.7 (6.0)
S1										
P1	6.2 (69.9)	0.0 (0.4)	1.8 (20.5)	0.0 (0.0)	0.0 (0.0)	0.0 (0.2)	0.3 (3.5)	0.0 (0.0)	0.0 (0.0)	0.5 (5.4)
P2	9.2 (35.3)	0.9 (3.5)	6.3 (24.1)	0.5 (2.1)	0.2 (0.8)	1.3 (4.9)	3.3 (12.6)	0.7 (2.5)	2.6 (10.0)	1.1 (4.1)
P3	7.7 (67.3)	0.1 (0.7)	1.8 (15.6)	0.0 (0.0)	0.0 (0.0)	0.1 (0.6)	0.8 (7.1)	0.1 (0.9)	0.1 (1.0)	0.8 (6.8)
P4	8.4 (39.6)	1.8 (8.4)	8.4 (39.8)	0.1 (0.4)	0.3 (1.6)	0.2 (0.7)	0.6 (2.7)	0.2 (0.8)	0.3 (1.5)	0.9 (4.4)
P5	4.4 (69.5)	0.0 (0.0)	0.9 (14.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.5)	0.4 (5.8)	0.0 (0.0)	0.0 (0.0)	0.6 (9.8)

P1: 4-8 February, 2022; P2: 9-13 February, 2022; P3: 14-16 February, 2022; P4: 17-18 February, 2022; P5: 19-20 February, 2022.

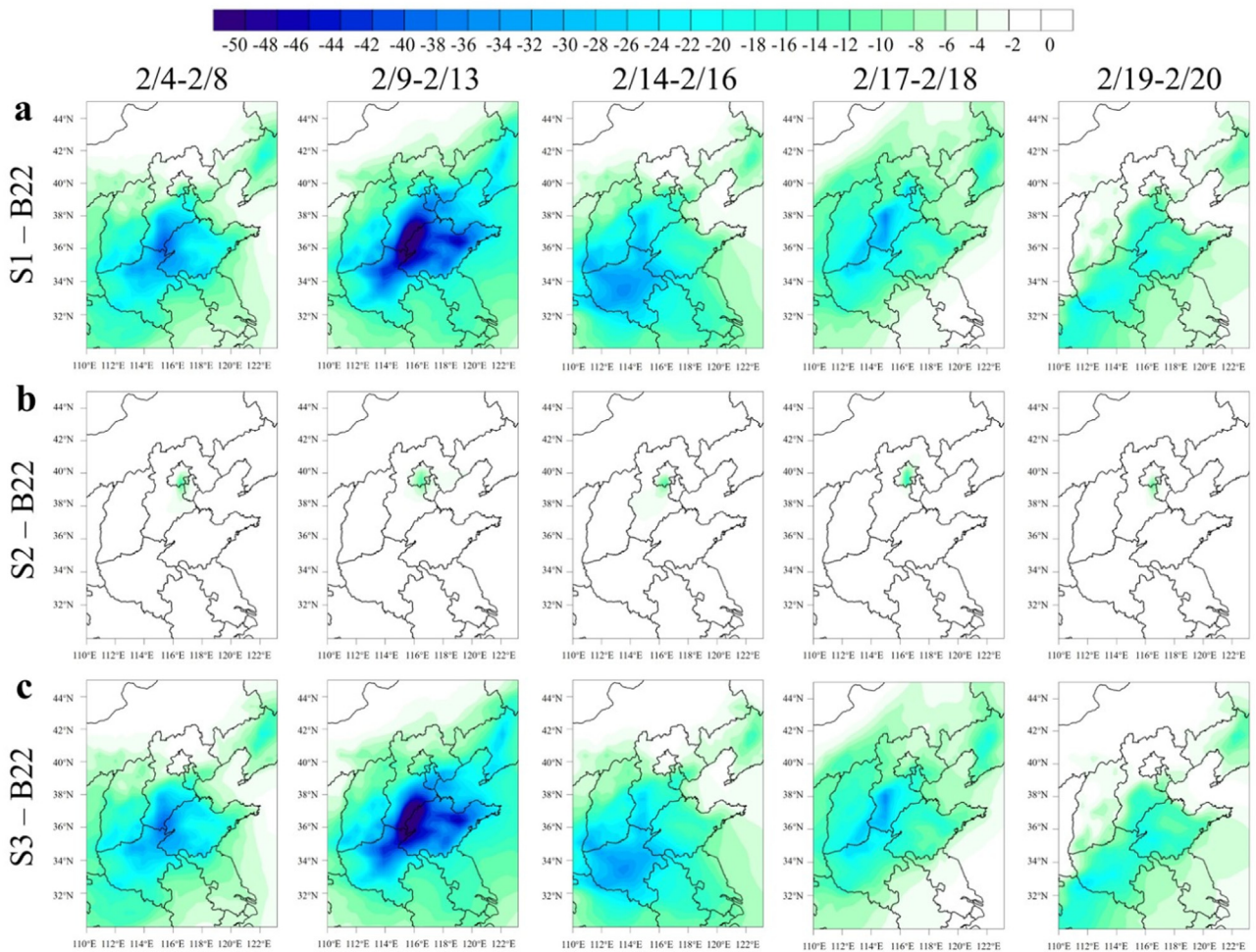


Fig. 8 – Spatial distributions of differences in mean $\text{PM}_{2.5}$ concentrations ($\mu\text{g}/\text{m}^3$) attributed to various emission control measures for the five different periods. (a) The differences between S1 and B22 cases. (b) The differences between S2 and B22 cases. (c) The differences between S3 and B22 cases.

tant role with the similar contributions. The emission reduction contributions were closely associated with the directions of the air mass transport trajectories. When the air masses mostly transported from the northwest, local emissions contributed more than 65% with the small absolute values of the contribution, so there was no need to reduce emissions in the surrounding regions unless emissions were controlled in advance for heavy pollution episodes (Gao et al., 2017b). In other situations, nonlocal emissions could effectively influence pollutant concentrations in Beijing through regional transports, which required scientific designs based on reliable weather and air quality forecasts. On the other hand, under the circumstance of local emission reductions, it was found that light pollution might occur in Beijing on February 10, and the daily average values of $PM_{2.5}$ on the other days were less than $75 \mu\text{g}/\text{m}^3$. This proves that to ensure the air quality of the 2022 Winter Olympics, it was necessary to carry out joint prevention and controls of regional air pollution on February 10 or even February 9, while other days could only implement local emission controls to decrease economic losses on the basis of the results of this study.

3. Conclusions

In this study, six simulation cases for different emission control scenarios were designed to assess the contributions of meteorology and emission control measures to the abatement of $PM_{2.5}$ in Beijing during the 2022 Winter Olympics. Although the model had varying degrees of overestimations and underestimations for different emission control scenarios in some cities, the simulations of S1 case with the designed emission reductions in Beijing and its surrounding areas were in a good agreement with observations, reproducing hourly variations of $PM_{2.5}$ concentrations in Beijing and other cities. The lower temperature, lower relative humidity, higher frequency of northwest winds, higher wind speeds, and higher planetary boundary layer heights provided favorable meteorological conditions for Beijing in comparison with meteorological conditions for the same periods in 2021. It was found that meteorological conditions in 2022 played a positive role in Beijing's blue skies with $PM_{2.5}$ decreasing by 6.9 and $11.8 \mu\text{g}/\text{m}^3$ relative to 2021 under the scenarios with and without emission reductions, respectively. In terms of emission reduction contributions, the average $PM_{2.5}$ concentrations in Beijing decreased by $13.0 \mu\text{g}/\text{m}^3$. The implementation of emission reduction measures in Beijing and its surrounding regions led to a reduction of Beijing's $PM_{2.5}$ by 7.2 and $5.8 \mu\text{g}/\text{m}^3$, respectively, indicating that local emission reduction measures played a more important role. By applying backward trajectory analysis method, it was found that the prevailing northwesterly air masses dominated during the cleaning periods, while air masses from the east-northeast and west-southwest were tightly associated with the potential pollution periods. Local emissions were the primary contributor during the cleaning periods (P1, P3, and P5), accounting for 69.9% to 67.3% under the emission reduction scenario. During the potential pollution periods (P2 and P4), especially when $PM_{2.5}$ concentrations increased, the contributions of regional transports became more significant, accounting for 64.7% to 60.4%. The analyses of the impacts of

local and nonlocal emission reductions at different periods indicate that local emission reductions always contributed a lot, especially in the potential pollution period, but nonlocal emission reductions made limited contributions during the cleaning periods and made contributions as much as local emission reductions during the potential pollution periods. Results suggest that regional joint prevention and controls could effectively reduce $PM_{2.5}$ concentrations when polluted events occurred in Beijing, but it is necessary to scientifically design the times, regions and control intensities for the joint prevention and controls to have best effectiveness for both economic and blue sky.

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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