Assessment of Meteorological Impact and Emergency Plan for a Heavy Haze Pollution Episode in a Core City of the North China Plain

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ABSTRACT

The Beijing-Tianjin-Hebei region, characterized by frequent episodes of severe haze pollution during winter, is recognized as one of the key regions requiring air pollution control. To reduce the effects of severe pollution, early warning and emission reduction measures should be executed prior to these haze episodes. In this study, the efficacy of emission reduction procedures during severe pollution episodes was evaluated using the Weather Research and Forecasting model coupled with chemistry (WRF-Chem). To provide feedback and optimize emergency emission reduction plans, a pollution episode that occurred during the period of December 20–26, 2015, which was characterized by a high warning level, long warning period, and integrated pollution process, was selected as a case study to determine the influence of meteorological conditions and the effects of mitigation measures on heavy haze pollution episodes. Adverse meteorological conditions were found to increase PM_{2.5} concentrations by approximately 34% during the pollution episode. Moreover, the largest contributor to the episode was fossil fuel combustion, followed by dust emission and industrial processes; the first two factors play a significant role in most districts in Tianjin, whereas the third more strongly affects the adjoining districts and Binhai District. Emission reduction for industrial sources and domestic combustion more obviously decreases PM_{2.5} concentrations during the pollution dissipation stage than the pollution accumulation stage. Thus, different mitigation measures should be adopted in different districts and during different pollution stages. An approximate decrease of 18.9% in the PM_{2.5} concentration can be achieved when an emergency plan is implemented during the red alert period for heavy haze pollution episodes.

Keywords: WRF-Chem; Mitigation measures; PM_{2.5}; Early warning.

INTRODUCTION

PM_{2.5}, also known as fine particulate matter, has an aerodynamic diameter of less than 2.5 μm and plays an important role in atmospheric visibility, human health, and climate change (Lim *et al.*, 2012). Regional haze with extremely high PM_{2.5} concentrations has become the primary air quality problem in China, especially in the Beijing-Tianjin-Hebei (BTH) region. Severe haze pollution episodes have been frequently observed over the BTH region, especially during winter (Wang *et al.*, 2014c; Han *et al.*, 2015).

The Ministry of Environmental Protection of China reported that six of the ten most polluted cities from January to December 2017 were located in the BTH region (EEPRC, 2018). The severe air pollution in the BTH region requires urgent attention. The variations and uncertainties in the emissions, species compositions, spatial and temporal resolution, and distribution among various emission sectors in the BTH region cause complexity in the regional formation and distribution of PM_{2.5}.

Tianjin is a crucial city in the BTH region, which is the most severely polluted region in China. Tianjin, which is located at the west of the Bohai Sea and enclosed by Beijing and Hebei, is the largest coastal city and one of the most polluted cities in northern China. Tianjin is a typical metropolis in northern China with a population of 15.47 million, a land area of approximately 11,946 km², and more than 2.85 million vehicles as of 2015. Moreover, Tianjin is also a large industrial city whose gross domestic product (GDP) was 1653.8 billion RMB in 2015. It ranked third in China according to GDP (CSP, 2016; CSPT, 2016; TJSP, 2016).

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The major industries in Tianjin include the port, petrochemical, iron and steel, and chemical industries. Moreover, the major energy resources consumed in Tianjin include coal, coke, crude oil, fuel oil, gasoline, kerosene, diesel oil, natural gas, and electric power. According to the Natural Bureau of Statistics (CSP, 2018), approximately 47.3 million tons of coal and 15.44 million tons of crude oil were consumed in Tianjin in 2017, which resulted in large amounts of gaseous pollutant emissions.

However, previous studies have revealed that the causes and characteristics of air pollution in Beijing, Tianjin, and Hebei differ (Gu *et al.*, 2011; Wang *et al.*, 2013, 2014b; Chen *et al.*, 2017; Liu *et al.*, 2018). Huang *et al.* (2017) determined that secondary inorganic aerosol was the largest source of $PM_{2.5}$ in the BTH region (29.2–40.5%). Moreover, motor vehicle exhaust was the second largest source of $PM_{2.5}$, especially in Beijing (24.9%). Furthermore, coal combustion was also a large source of $PM_{2.5}$ in Tianjin (12.4%) and Shijiazhuang (15.5%), with particular dominance during winter. Han *et al.* (2018) indicated that Hebei and Shandong were the dominant sources for $PM_{2.5}$ over the North China Plain (NCP). However, Beijing and Tianjin are usually affected by local emissions. Wang *et al.* (2017) applied Particulate Matter Source Apportionment Technology (PSAT) in the Comprehensive Air Quality Model with Extensions (CAMx). They determined that local emissions contributed 83.6% of the total $PM_{2.5}$ concentration in the urban center of Beijing and that the local contribution can more easily cause a sharp increase or reduction in the $PM_{2.5}$ concentration in central Beijing than in other locations. Peng *et al.* (2019) identified coal combustion, biomass burning, and vehicle emission and determined the presence of sea salt, nitrate sources, sulfate sources, and crustal dust sources as major sources of $PM_{2.5}$ in Tianjin by using three different methods. Liu *et al.* (2018) indicated that crustal dust, secondary sources, vehicle emissions, coal combustion, and industrial emissions were the primary sources of $PM_{2.5}$ in Shijiazhuang. Therefore, air pollution prevention and control should be

adapted to local conditions. Because of the various emission features and urban constructions in different cities, the “One City, One Policy” project was proposed to establish the targeted and possible measures for reducing and limiting emissions in each city. Due to the requirement of urgent air quality control, the effectiveness of air quality control managements and heavy pollution emergency plans should be dynamically evaluated. Moreover, feedbacks should be provided and final decisions should be optimized.

Severe pollution episodes in Tianjin mainly occur during winter. Thus, we selected December as an example for this study. Fig. 1 presents the air quality index (AQI) (MEP, 2012) and daily primary pollutants in December 2015. The moderately to seriously polluted days account for 64.5% of the entire month, and the days with $PM_{2.5}$ as the primary pollutant account for 82.1% of the entire month. Thus, air pollution is extremely severe and characterized by fine particles in Tianjin during winter.

Currently, studies on the emission reduction effect are mainly based on two methods—observation and air quality model methods. The observation method is widely used (Liu *et al.*, 2013; Wang *et al.*, 2014a). However, the use of the observation method alone has some limitations, such as the inability to forecast and assess measures that have not been implemented or are unfinished and the inability to rule out the effects of meteorological conditions and background concentrations. The air quality model method has the advantages of scenario analysis and has a good ability to predict the temporal-spatial distribution of pollutants (Wang, 2014; Li *et al.*, 2015; Han *et al.*, 2016). Han *et al.* (2016) used the Regional Atmospheric Modeling System model and Models-3 Community Multiscale Air Quality (CMAQ) model (RAMS–CMAQ) with a zero-out sensitivity test for conducting source sensitivity approaches for $PM_{2.5}$. They concluded that residential and industrial sources were the largest contributors to $PM_{2.5}$ in the NCP regions. Li *et al.* (2015) used the Weather Research and Forecasting (WRF) model and CMAQ model (WRF–CMAQ) to simulate and

Fig. 1. AQI and daily primary pollutants in December in Tianjin. *I*, *II*, *III*, *IV*, *V*, *VI* represent different air quality index, where *I* represents well, *II* represents fine, *III* represents mild pollution, *IV* represents moderate pollution, *V* represents severe pollution and *VI* represents serious pollution (MEP, 2012).

action plan (2013–2017). The study concluded that under weak, medium, and strong emission reduction scenarios, the evaluate the effect of air quality improvement in the Yangtze River Delta region after the implementation of a clean air average annual concentration of $PM_{2.5}$ in the Yangtze River Delta region decreased by 8.7%, 15.9%, and 24.3%, respectively. However, the aforementioned studies mainly focused on the overall effect of emission reduction and paid less attention to the effect of early warning and emission reduction measures of detailed sectors on the temporal-spatial distribution during severe haze episodes.

In this study, the WRF model coupled with chemistry (WRF-Chem) was applied to evaluate the effect of emission reduction measures during severe pollution episodes. The influence of different factors on the air quality, feedback, and optimized emission reduction plans was analyzed in this study. The roles of meteorological conditions and different emission categories, such as fossil fuel combustion, industrial processes, transport, solvent use, dust, agriculture, biomass burning, storage, and waste disposal, were investigated by conducting sensitivity experiments in terms of the $PM_{2.5}$ mass burden. The effects of different emission reduction scenarios were evaluated under different pollution levels.

MODEL DESCRIPTION, INPUT DATASETS, AND PROTOCOLS

Configurations and Domain of the WRF-Chem Model

WRF-Chem is an online-coupled three-dimensional (3D) air quality model that has been widely used in recent years (Fast *et al.*, 2006; Han *et al.*, 2008; Misenis and Zhang, 2010; Yan, 2013; An *et al.*, 2013; Wu *et al.*, 2013; Zhang *et al.*, 2013). The model considers the feedback between the meteorology of a region and aerosols and thus can simulate the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorology (Grell *et al.*, 2005). In this study, WRF-Chem (version 3.7) was used for simulating the distribution of gaseous pollutants (e.g., SO_2 , NO_x , CO, and O_3), $PM_{2.5}$, PM_{10} , and their major components in December 2015. A typical severe haze episode from December 20–26, 2015, was selected to assess the effects of major emission reduction measures in Tianjin.

As displayed in Fig. 2, the model domain includes a horizontal grid spacing of 36 km that covers most of the area of China (Domain 1) and a nested-domain horizontal grid spacing of 12 km that covers northeastern China, encompassing Beijing, Tianjin, Hebei, Henan, Shandong, and Shanxi

Fig. 2. WRF-Chem modeling domains at a horizontal grid resolution of 36 km for East Asia (Domain 1 with 164×97 cells) and at 12 km for an area in northern China (Domain 2 with 126×144 cells) and the location of the 14 sites used for evaluating in Tianjin.

(Domain 2). Twenty-three vertical levels were set up from the surface to the model lid (~100 mb) for the WRF-Chem model. The corresponding sigma levels were 1.000, 0.995, 0.988, 0.980, 0.970, 0.956, 0.938, 0.916, 0.893, 0.868, 0.839, 0.808, 0.777, 0.744, 0.702, 0.648, 0.582, 0.500, 0.400, 0.300, 0.200, 0.120, 0.052, and 0.000.

A summary of the major chemical and physical parameters in this study is presented in Table 1. The gas-phase chemistry and aerosol modules include the Carbon-Bond Mechanism version Z (CBMZ) (Zaveri and Peters, 1999) and 8-bin MOSAIC aerosol, which include some aqueous reactions (Zaveri *et al.*, 2008). The major physical parameterization options used are the Goddard shortwave radiation scheme (Chou *et al.*, 1998), the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer *et al.*, 1997), the Yonsei University planetary boundary layer (PBL) scheme (YSU) (Hong *et al.*, 2006), and the Grell 3D ensemble cumulus parameterization scheme (Grell and Devenyi, 2002). The biogenic emissions employed the Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2 (Guenther *et al.*, 2006).

For the meteorology field simulation, the National Center for Environmental Prediction (NCEP) Final Operational Global Analysis datasets were used as the initial and boundary conditions and the NCEP Automated Data Processing surface and upper air datasets were used as four-dimensional data assimilation for WRF-Chem model.

The initial chemicals for Domain 1 include the default chemical profiles in WRF-Chem with 7 days (November 24–30, 2015) of pre-simulation to minimize the influence of the initial conditions. The model's default profile was used as the chemical boundary condition.

Emission Inventory

In this study, a combination of the “bottom-up” and “top-down” methods was used to establish the anthropogenic emissions of eight species, namely sulfur dioxide (SO₂), nitrogen oxide (NO_x), carbon monoxide (CO), nonmethane volatile organic compounds (NMVOCs), ammonia (NH₃),

carbon dioxide (CO₂), coarse particulate matter (PM₁₀), and PM_{2.5}. The 2013 local emission inventory for Tianjin pertaining to 10 sectors was provided by Tianjin Eco-Environmental Monitoring Center. These sectors are fossil fuel combustion (three subsectors: domestic combustion, industrial boiler combustion, and power plant combustion), industrial processes, transport, solvent use, dust, agriculture, biomass burning, storage and transport, waste disposal, and other sectors. The Multi-resolution Emission Inventory for China (MEIC) for 2012 was used to determine the anthropogenic emissions in other parts of China except in Tianjin. The data for five sectors, namely industry, power plant, transport, residential, and agriculture, were obtained.

Fig. 3 displays the emission inventory distribution of SO₂, NO_x, PM_{2.5}, and CO in Tianjin. The PM_{2.5} emission intensity was the highest in central districts, followed by adjoining districts such as Jizhou District, Wuqing District, and Ninghe District. The locations of different districts are illustrated in Fig. 2. The spatial distributions of SO₂ and CO emissions were similar to that of PM_{2.5} emission, which is mainly consistent with distributions such as the residential coal combustion, steel, and cement industrial distributions. Industrial processes were the major sources of SO₂ and NO_x emissions in Dongli District and Ninghe District and accounted for more than 90% of the total SO₂ and NO_x emissions. Residential coal combustion emissions accounted for more than 50% of the total SO₂ and CO emissions in Wuqing District and Jizhou District. The NO_x emission intensity was higher in central districts and Binhai District than in adjoining districts, followed by outer suburban districts. This finding indicated a higher amount of vehicle emissions in the central districts and Binhai District than in other districts. The Port of Tianjin has the fifth highest throughput in the world, which leads to high emissions of diesel vehicles in Binhai District. Maritime emissions accounted for 76.8% of the total NO_x emissions in Binhai District. Moreover, in central districts, heavy-duty diesel vehicles were forbidden and nonlocal vehicles were restricted during the peak time. Thus, these types of vehicles can only

Table 1. WRF-Chem model configurations used in this study.

Attribute	Parameterization options
Gas-phase chemistry	Carbon-Bond Mechanism version Z (CBMZ) (Zaveri and Peters, 1999)
Photolysis	Madronich F-TUV (Madronich and Flocke, 1993)
Aerosol module	8-bin MOSAIC aerosol including some aqueous reactions (Zaveri <i>et al.</i> , 2008)
Urban surface	Urban canopy model (Ikeda and Kusaka, 2010)
Shortwave radiation	Goddard shortwave scheme (Chou <i>et al.</i> , 1998)
Longwave radiation	Rapid Radiative Transfer Model (RRTM) scheme (Mlawer <i>et al.</i> , 1997)
Land surface	National Center for Environmental Prediction, Oregon State University, Air Force, and Hydrologic Research Lab's (NOAH) Land Surface Model (Ek <i>et al.</i> , 2003)
Surface layer	Monin-Obukhov (Janjić Eta) scheme (Janjić, 2001)
Planetary boundary layer (PBL)	Yonsei University Scheme (YSU) (Hong <i>et al.</i> , 2006)
Cumulus	Grell 3D ensemble (Grell and Devenyi, 2002)
Microphysics	Purdue Lin (Chen and Sun, 2002)
Biogenic emissions	Model of Emissions of Gases and Aerosols from Nature (MEGAN) version 2 (Guenther <i>et al.</i> , 2006)
Dust emissions	GOCART dust emissions (Shaw <i>et al.</i> , 2008)
Sea-salt emissions	Gong <i>et al.</i> (2003)

Fig. 3. Emission intensity of (a) SO₂, (b) NO_x, (c) PM_{2.5}, and (d) CO in Tianjin (unit: t a⁻¹).

be driven in the adjoining districts. The emissions due to transportation were the major emissions in central districts and accounted for 99.6% of the total NO_x and CO emissions.

EVALUATION OF THE MODEL PERFORMANCE

The observational datasets used for model evaluation in this study are presented in Table 2. The temperature at 2 m (T2), water vapor mixing ratio at 2 m (Q2), wind speed at 10 m (WS10), wind direction at 10 m (WD10), and daily cumulative precipitation data for December 2015 from the National Climate Data Center (NCDC) integrated surface database ([http://www.ncdc.noaa.gov/data-access/quick-](http://www.ncdc.noaa.gov/data-access/quick-links#ghcn)

[links#ghcn](http://www.ncdc.noaa.gov/data-access/quick-links#ghcn)) for 371 sites were used to evaluate the meteorological simulations.

PM (PM_{2.5} and PM₁₀) and trace gases (SO₂, NO₂, and CO) were evaluated using the observational datasets presented in Table 2. The average hourly concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂, and CO at 14 monitoring sites in Tianjin were obtained from the China National Environmental Monitoring Center (CNEMC) dataset (four sites in the central districts, four sites in the adjoining districts, five sites in suburban districts, and one site in Binhai District). The locations and descriptions of these sites are presented in Table 3 and Fig. 2.

Table 4 presents the overall statistics of the meteorological simulations for Domain 1 at a 36-km resolution and for

Table 2. Observational datasets used for model evaluation in this study.

Datasets	NCDC	CNEMC
Data type	Meteorology	Air quality
Variable	T2, Q2, WD10, WS10, Precipitation	PM _{2.5}
Site number	371	496
Time period	December 2015	December 2015
Data source	http://www.ncdc.noaa.gov/data-access/quick-links#ghcn	http://beijingair.sinaapp.com/

Table 3. Location and description of 14 sites used for evaluating in Tianjin.

No.	District	Site	Description
1	Nankai (urban)	Binshui West Road	surrounded by residential and commercial building without apparent industrial emissions
2	Hongqiao (urban)	Qinjian Road	surrounded by residential and commercial building without apparent industrial emissions
3	Hedong (urban)	Dazhi No. 8 Road	surrounded by residential and commercial building without apparent industrial emissions
4	Hexi (urban)	Qianjin Road	surrounded by residential and commercial building without apparent industrial emissions
5	Beichen (adjoining districts)	Huaihe Road	surrounded by residential and commercial building with apparent industrial emissions
6	Dongli (adjoining districts)	Yuejin Road	surrounded by residential and commercial building with apparent industrial emissions
7	Jinnan (adjoining districts)	Jingu Road	surrounded by residential and commercial building with apparent industrial emissions
8	Jixian	Donghuan Road	dominated by agriculture and residential source
9	Jinghai	Tuanbowa	dominated by agriculture and residential source without apparent industrial emissions
10	Ninghe	Binshui East Road	dominated by agriculture and residential source; there are also apparent iron and steel industrial emissions
11	Xiqing (adjoining districts)	Haitai Develop Second Road	surrounded by residential and commercial building with apparent industrial emissions
12	Binhai	Hanbei Road	dominated by heavy industrial emissions due to petrochemical, iron and steel, and chemical processes
13	Baodi	Baobai Road	dominated by agriculture and residential source
14	Wuqing	Yongyang West Road	dominated by agriculture and residential source

Domain 2 at a 12-km resolution according to comparisons with the NCDC dataset. The mean bias (MB), root mean square error (RMSE), normalized mean bias (NMB), and normalized mean error (NME) were defined in a study by Zhang *et al.* (2006). T2 agrees well with the observations in which MBs range from 0 to 0.2°C and NMBs range from 0.6% to −11.4% for both domains. Although T2 is marginally underestimated in Domain 2, T2 is within the criteria of MB at $\leq \pm 0.5$ K (Tesche *et al.*, 2001). Q2 is overestimated for the MBs of 0.0004 kg kg^{−1} for Domain 1 and 0.0000 kg kg^{−1} for Domain 2. Both values are within the criteria of MB at $\leq \pm 1$ g kg^{−1}. Wind speed is overestimated for MBs at 0.6 m s^{−1} for Domain 1 and 0.1 m s^{−1} for Domain 2. The predictions for Domain 1 are beyond the criteria for MB at $\leq \pm 0.5$ m s^{−1} (Emery *et al.*, 2001). This result was obtained possibly because the finite-difference model is one of the most accepted medium-range weather forecasting models but it cannot suitably describe atmospheric motions smaller than the grid size (Wang *et al.*, 2011). However, the predictions for Domain 2 meet the criteria for MB at $\leq \pm 0.5$ m s^{−1}. The

model predictions for wind directions are overestimated with MBs of 2.6° for Domain 1 at a 36-km resolution and underestimated with MBs of −0.9° for Domain 2 at a 12-km resolution. These results agree well with the observations, and the predictions at both resolutions are within the criteria of MB of $\leq \pm 10^\circ$ (Emery *et al.*, 2001). The daily cumulative precipitation was significantly underestimated for both domains, with MBs of −10.6 mm and −24.0 mm for Domain 1 at a 36-km resolution and Domain 2 at a 12-km resolution, respectively.

The performance statistics based on comparisons with the CNEMC dataset, including the NMB, NME, mean fractional bias (MFB), and mean fractional error (MFE), for PM_{2.5}, PM₁₀, SO₂, NO₂, and CO simulations at 496 national monitoring stations in 74 major cities in China for Domain 1 at a 36-km resolution and Domain 2 at a 12-km resolution are presented in Table 5. The MFB value is within $\pm 60\%$ and the MFE value is within 75% in this study. These values are considered to represent a satisfactory performance according to the guidelines (Boylan, 2005). As presented in Table 5,

Table 4. Overall statistics for the meteorological simulations.

		T2 (°C)	Q2 (kg kg ⁻¹)	WD10 (degree)	WS10 (m s ⁻¹)	Precipitation (mm)
Domain 1	N pairs of data	348,214	232,308	289,447	333,867	6416
	Obs.	5.8	0.0048	205.8	2.8	13.6
	Mod.	5.8	0.0052	207.1	3.4	3.0
	MB	0.0	0.0004	2.6	0.6	−10.6
	RMSE	3.1	0.0011	67.9	2.2	37.8
	NMB (%)	0.6%	8.7%	1.3%	19.5%	−77.7%
	NME (%)	38.9%	16.4%	24.5%	56.4%	90.9%
Domain 2	N pairs of data	35,170	18,805	30,397	32,965	746
	Obs.	−1.8	0.0024	217.0	2.6	24.6
	Mod.	−2.0	0.0024	210.5	2.7	0.6
	MB	−0.2	0.0000	−0.9	0.1	−24.0
	RMSE	2.3	0.0004	60.4	1.6	51.2
	NMB (%)	−11.4%	0.1%	−0.4%	5.2%	−97.5%
	NME (%)	−97.1%	13.3%	19.9%	44.1%	98.7%

Table 5. Performance statistics for the chemical concentrations between simulations and observations for the 496 sites in China.

		PM _{2.5}	PM ₁₀	SO ₂	NO ₂	CO
		(μg m ⁻³)				(mg m ⁻³)
Domain 1	N pairs of data	976,779	893,285	979,990	979,342	975,732
	Obs.	79.1	120.4	38.6	43.5	1.5
	Mod.	105.8	111.0	61.8	57.5	1.5
	MB	26.7	−9.4	23.2	14.0	−0.1
	NMB (%)	33.7%	−7.8%	60.2%	32.2%	−3.5%
	MFB (%)	28.2%	−6.2%	13.7%	9.5%	−10.3%
	MFE (%)	74.7%	64.2%	92.2%	73.0%	65.9%
Domain 2	N pairs of data	422,460	392,727	423,651	423,816	422,585
	Obs.	107.0	162.8	55.5	53.5	1.9
	Mod.	140.6	144.4	149.1	80.3	2.4
	MB	33.6	−18.4	93.6	26.9	0.5
	NMB (%)	31.4%	−11.3%	168.7%	50.3%	25.6%
	MFB (%)	25.2%	−12.4%	30.8%	28.3%	−1.4%
	MFE (%)	74.3%	66.3%	101.8%	73.5%	72.6%

the simulated PM_{2.5} concentrations were marginally higher than the observed concentrations, with MBs and NMBs of 26.7 μg m⁻³ and 33.7% for Domain 1 and 33.6 μg m⁻³ and 31.4% for Domain 2, respectively. However, the predictions for Domain 1 and Domain 2 meet the criteria of MFB at ≤ ±60% and MFE at ≤ ±75%. PM₁₀ data were underestimated, with the MBs of −9.4 and −18.4 μg m⁻³ for Domain 1 at a 36-km resolution and Domain 2 at a 12-km resolution, respectively. Both values are within the criteria of MFB (−6.2% for Domain 1 and −12.4% for Domain 2) and MFE (64.2% for Domain 1 and 66.3% for Domain 2). As for trace gases, SO₂ was significantly overestimated for both domains, with MBs of 23.2 and 93.6 μg m⁻³ for Domains 1 and 2, respectively. Both values are within the criteria for MFB at ≤ ±60% (MFE is 13.7% for Domain 1 and 30.8% for Domain 2) and exceed the criteria for MFE at ≤ ±75% (MFE is 92.2% for Domain 1 and 101.8% for Domain 2). The results are similar to those of some previous studies (Wang et al., 2014b; Wang et al., 2016). The results imply that large uncertainties are caused in spatial allocations of the emissions into a grid with a low resolution. These uncertainties may

result in overestimation of the urban SO₂ emissions if the population density and GDP are used to spatially allocate the industrial and fossil fuel combustion emissions (Wang et al., 2014b). Moreover, uncertainties exist in the model's description of the conversion process from SO₂ to sulfate (Wang et al., 2016). NO₂ was also overestimated in both domains; however, this overprediction was not as significant as that of SO₂, with NMBs of 32.2% for Domain 1 and 50.3% for Domain 2. The MFBs and MFEs of NO₂ were within the criteria (MFB ≤ ±60% and MFE ≤ ±75%). The underprediction of CO (with an MB of −0.1 mg m⁻³ and NMB of −3.5%) for Domain 1 and overprediction (with an MB of 0.5 mg m⁻³ and NMB of 25.6%) for Domain 2 meet the criteria over the two domains.

To evaluate the performance statistics of the PM_{2.5} concentrations between the simulations and observations, the observed average hourly PM_{2.5} concentrations at 14 monitoring sites in different districts in Tianjin were compared with the base simulations for December 2015. The overall simulated (Domain 2) and observed hourly concentrations of PM_{2.5} for the 14 sites are depicted in Fig. 4. The model

Fig. 4. Comparison between simulated and observed hourly $PM_{2.5}$ concentration at the 14 sites in Tianjin.

Fig. 4. (continued).

appropriately reproduced the $PM_{2.5}$ concentrations for the suburban districts and Binhai District, including Donghuan Road, Hanbei Road, Baobai Road, and Yongyang West Road sites. The $PM_{2.5}$ concentrations for the Huaihe Road sites in Beichen District were significantly overestimated, especially during the peak that occurred on December 8–12 and 20–26, 2015. The simulations for the central districts and most of the adjoining districts generally agreed with the observations of $PM_{2.5}$ during most days of the month. However, a relative overestimation occurred during the heavy pollution episode. One reason for the overestimation may be that the mitigation measures adopted in the industry after 2013 were not considered. Another reason is that the

spatial allocation of emissions included large uncertainties. In recent years, most industrial plants have been removed from urban Tianjin. Thus, space allocation based on the population density for some sectors results in inconsistencies between real and estimated emissions.

EVOLUTION OF THE EFFECT OF METEOROLOGICAL CONDITIONS

Adverse meteorological conditions are crucial external factors that lead to severe pollution episodes. The same emissions as a base case as well as different meteorological conditions a week before the base case (BW) and a week

after the base case (AW) were used to simulate the contribution of adverse meteorological conditions during severe pollution episodes.

Fig. 5 presents the temporal variation in the meteorological parameters, such as WD10, WS10, T2, Q2, the planetary boundary layer height (PBLH), surface pressure (PSFC), and $PM_{2.5}$ concentrations for December 2015. The results in Fig. 5 indicate that the combined influence of a relatively high water vapor mixing ratio, low wind speed, low temperature, low PBLH, and low pressure caused a 33.5% increase in the $PM_{2.5}$ concentration during the severe pollution episode of December 20–26, 2015. The wind speed of the base case decreased by 0.91 and 0.12 $m s^{-1}$ compared with the BW and AW cases, respectively. The temperature for the base case exhibited a 0.91°C decrease and 0.75°C increase compared with the values for the BW and AW cases, respectively. For the base case, the water vapor mixing ratio increased by 0.0006 and 0.0005 $kg kg^{-1}$ over the BW and AW cases, respectively. Then, the PBLH decreased by 249.5 and 39.1 m for the base case compared with the PBLH for the BW and AW cases, respectively. The surface pressure decreased the least among the meteorological parameters. The base case was 3.9 and 6.8 kPa lower than the BW and AW cases, respectively.

Fig. 6 displays the variation in the $PM_{2.5}$ concentrations due to different meteorological conditions. The contributions from meteorology were estimated by calculating the differences between the base case and the other cases. The $PM_{2.5}$ concentration was in the range of 58.2–483.3 $\mu g m^{-3}$ during the BW case that occurred from December 13 to 19, which was approximately 17.9–78.3% of the baseline $PM_{2.5}$

concentrations. The contribution of the baseline $PM_{2.5}$ concentration was in the range of 8.2–73.2% for the AW case that occurred from December 27 to 31. In general, compared with the BW and AW cases, adverse meteorological conditions caused a 33.5% (the averages are 41.0% and 25.9% for the BW and AW cases, respectively) increase of the $PM_{2.5}$ concentrations during December 20–26. Therefore, the considerable contribution by adverse meteorological conditions should not be neglected.

Overall, the unfavorable meteorological conditions caused a 101.3 $\mu g m^{-3}$ increase in the $PM_{2.5}$ concentration during the severe pollution episode.

SIMULATION SCENARIO DESIGN AND ASSESSMENT OF EMISSION REDUCTION

Simulation Scenario Design

The emergency plan for heavy pollution episodes in Tianjin includes three mitigation measure classes (TJMPG, 2016). These classes are 40%, 30%, and 20% reductions in the fossil fuel combustion, industrial processes, transport, solvent use, and dust during red, orange, and yellow alerts, respectively. Twelve experiments with reduction in each emission category (nine major sectors and three subsectors) for the red alert scenario were conducted for Domain 2 to evaluate the influence of the major emission reduction measures on air quality (Table 6).

Source Assessment

The effect of each emission reduction scenario on the ambient $PM_{2.5}$ concentrations during a typical severe pollution

Fig. 5. Temporal variation of meteorological parameters and $PM_{2.5}$ concentrations.

Fig. 6. The variation of daily PM_{2.5} concentrations due to different meteorological conditions (BW: meteorological conditions from December 13 to 19; AW: meteorological conditions from December 27 to 31).

Table 6. Configurations of the simulation scenarios.

No.	Scenario	Description
1	Base	Base
2	BA40	Only fossil fuel combustion reduced by 40% in Tianjin
3	IP40	Only industrial processes reduced by 40% in Tianjin
4	TR40	Only transport reduced by 40% in Tianjin
5	SA40	Only solvent use reduced by 40% in Tianjin
6	DU40	Only dust reduced by 40% in Tianjin
7	AG40	Only agriculture reduced by 40% in Tianjin
8	BO40	Only biomass burning reduced by 40% in Tianjin
9	ST40	Only storage and transport reduced by 40% in Tianjin
10	RP40	Only waste disposal reduced by 40% in Tianjin
11	BD40	Only domestic combustion in a fixed source of fossil fuel combustion reduced by 40% in Tianjin
12	BI40	Only industrial boiler combustion in a fixed source of fossil fuel combustion reduced by 40% in Tianjin
13	BP40	Only power plant combustion in a fixed source of fossil fuel combustion reduced by 40% in Tianjin

episode was simulated using the WRF-Chem model. The contributions (Eq. (1)) and change ratio (Eq. (2)) resulting from 40% emission reductions are illustrated in Figs. 7 and 8.

$$C_{s,i} = \frac{C_b - C_i}{C_b} \times 100\% \quad (1)$$

$$CR_{s,i} = \frac{C_b - C_i}{\sum_{k=1}^n (C_b - C_i)} \times 100\% \quad (2)$$

where $C_{s,i}$ is the contribution of source i to PM_{2.5}, C_b is the baseline PM_{2.5} concentration, C_i is the prediction made in the emission reduction scenario of source i , and $CR_{s,i}$ represents the change ratio of source i to the total reduction of PM_{2.5}.

An 18.9% decrease in the total PM_{2.5} concentration was observed due to the summation of the emission reduction in the nine major sectors during the pollution episode. Among the nine sectors, fossil fuel combustion contributed the most

to PM_{2.5} and accounted for 8.5% of the total PM_{2.5} concentrations. Decreases of 3.4% and 5% were observed in the total PM_{2.5} concentrations due to reductions in the industrial boiler combustion and domestic combustion, respectively. Decreases of 5.3% and 4% were observed in the total PM_{2.5} concentrations due to the emission reduction pertaining to dust and industrial processes, respectively. The contribution of transport was 1% of the total simulated PM_{2.5} concentration. Moreover, the contributions of other sectors were all at low levels. In addition, it is worth noting that the contribution from meteorology was up to 41.0% for the total PM_{2.5} concentrations during the pollution episode, which indicates the importance of favorable meteorological conditions for improving the ambient air quality.

To understand the contribution variations in sector emission reduction under different pollution levels, the baseline PM_{2.5} concentrations and change ratio of PM_{2.5} concentrations caused by the emission reductions of nine major sectors are presented in Fig. 9. The change ratios of fossil fuel combustion and dust were relatively high when the PM_{2.5} concentrations were above 500 µg m⁻³, and the average change ratios were

Fig. 7. Simulated $PM_{2.5}$ concentrations for the base case and other cases.

Fig. 8. Change ratio of $PM_{2.5}$ concentration owing to 40% emissions reductions.

Fig. 9. Scatterplot of the baseline $PM_{2.5}$ concentrations and change ratio of $PM_{2.5}$ concentrations owing to the reductions in the nine major sector emissions in Tianjin.

12.2% and 7.0%, respectively. The change ratio caused by industrial processes retains a relatively high value as the $\text{PM}_{2.5}$ concentrations were in the range of $300\text{--}400\ \mu\text{g m}^{-3}$, and the average change ratio was 7.8%. The change ratio pertaining to transport was 1.2% and increasing marginally as the $\text{PM}_{2.5}$ concentrations increased above $400\ \mu\text{g m}^{-3}$. The change ratio pertaining to agriculture remained stable, which may be because NH_3 was underestimated in the emission inventory for all sectors except agriculture. The change ratio pertaining to industrial boiler and domestic combustions had peak values when the $\text{PM}_{2.5}$ concentrations were high. Moreover, the contributions from domestic combustion were considerably higher than those from industrial boiler combustion when the $\text{PM}_{2.5}$ concentrations were higher than $500\ \mu\text{g m}^{-3}$. This result occurred due to the large increase in energy consumption caused by winter heating systems. The remaining sectors maintained relatively low contributions regardless of whether the $\text{PM}_{2.5}$ concentrations were low or high.

Two stages were selected to further explore the underlying cause of the aforementioned phenomenon—the pollution accumulation stage (S1) and pollution dissipation stage (S2). The ventilation, a combined response of both the maximum mixing layer depth and transport wind speed (Huang *et al.*, 2018), and the $\text{PM}_{2.5}$ concentration during the episode are presented in Fig. 10. The average ventilation was $21.8\ \text{m}^2\ \text{s}^{-1}$ during S1 and up to $1497.5\ \text{m}^2\ \text{s}^{-1}$ during S2. The dust emission reduction effect did not vary with the pollution stage, which may be because most of the dust was primary coarse particulate matter. The effect of emission reduction for industrial sources (including industrial processes and industrial boiler combustion) and domestic combustion during the pollutant dissipation stage was superior to the effect during the pollutant accumulation stage. There may exist two

reasons for this phenomenon. First, the diffusion condition becomes favorable with an increase in ventilation, thus directly causing a decrease in the $\text{PM}_{2.5}$ and gaseous precursor (SO_2 , NO_x , and NH_3) concentrations. Second, secondary reactions occur with more difficulty during the dissipation stage than during the accumulation stage due to an improvement in the meteorological conditions (e.g., low relative humidity and high PBLH) during the dissipation stage.

Spatial Variation of the Emission Reduction Effect

Fig. 11 displays the relative contributions caused by different mitigation measures in the different districts of Tianjin. Beichen District exhibited the largest decrease in the $\text{PM}_{2.5}$ concentrations, followed by Dongli District and central districts. Fossil fuel combustion contributed to most of the nine major sectors in most districts of Tianjin except for Ninghe District and Binhai District. The decrease in fossil fuel combustion accounted for 39.3–68.3% of the total decrease in the $\text{PM}_{2.5}$ concentrations. The $\text{PM}_{2.5}$ concentrations decreased the most in Jizhou District and Wuqing District due to decrease in fossil fuel combustion, which accounted for 68.3% and 66.6% of the total decrease in $\text{PM}_{2.5}$ concentrations, respectively (compared with the results in Figs. 3(a) and 3(d)). The contribution of fossil fuel combustion reduction was followed by dust reduction, which accounted for 15.4–34.5% of the total decrease in $\text{PM}_{2.5}$ concentrations. The largest contribution of dust was observed in Baodi District, whereas the least contribution was observed in Ninghe District. Decreases in industrial process emissions had the highest contribution in Ninghe District and Binhai District, accounting for 58.2% and 50.7%, respectively, of the total decrease in the $\text{PM}_{2.5}$ concentrations, which play a dominant role in the two districts. This result is consistent with the high industrial emissions due to petrochemical, iron and steel, and chemical

Fig. 10. Influence of meteorological conditions on percentage of $\text{PM}_{2.5}$ concentration decrease caused by different source emissions reductions.

Fig. 11. Regional difference caused by different sectors in Tianjin.

processes in Binhai District and due to the iron and steel industrial emissions in Ninghe District (compared with the results shown in Figs. 3(c) and 3(d)). Moreover, 33.8% of the total decrease in the $PM_{2.5}$ concentrations in Jinnan District is also prominent. The remaining regions in Tianjin contributed to 5.6–18.7% of the total decrease in the $PM_{2.5}$ concentrations. Moreover, the relatively obvious contribution of transport occurred in Beichen District and Dongli District, followed by the central districts. Transport contributed to 5.7–8.5% of the $PM_{2.5}$ in the aforementioned three regions, which may be due to the high heavy-duty diesel vehicle emissions in the two adjoining districts and the emissions from a high number of private vehicles in the central districts (compared with the results presented in Fig. 3(b)). Agriculture plays a significant role in Jinghai District and Jinnan District and contributed to 6% and 3.7% of the total decrease in $PM_{2.5}$ concentrations, respectively. In the other districts, agriculture contributed to between –1.1% and 1.6% of the decrease in $PM_{2.5}$. The decrease in $PM_{2.5}$ caused by the reduction of emissions from solvent use, biomass burning, storage and transport, and waste disposal were minimal in all districts of Tianjin.

The relative contributions of the three subsectors of fossil fuel combustion—industrial boiler combustion, domestic combustion, and power plant combustion—to the $PM_{2.5}$ concentrations for different districts in Tianjin are illustrated in Fig. 11. Significant regional differences were observed at different sites. For Jizhou District, Baodi District, and Wuqing District, domestic combustion was the major contributor to the total fossil fuel combustion and accounted for 81.4–92.5% of the total fossil fuel combustion contribution. Domestic combustion accounted for 75.0% and 63.3% of the total fossil fuel combustion contribution in Jinghai District and Xiqing District, respectively. Industrial boiler combustion plays a significant role in Binhai District and Beichen District and accounted for 57.2% and 54.3% of the three subsectors,

respectively. In the rest of Tianjin, the contributions from domestic combustion were similar to the contribution from industrial boiler combustion. However, the contributions from domestic combustion were marginally higher than those from industrial boiler combustion. The emission reduction of power plant combustion was not significant for all sites in Tianjin.

In summary, mitigation measures for dust should be adopted in all districts of Tianjin. Moreover, fossil fuel combustion should be preferentially reduced in most districts of Tianjin, especially in Jizhou District and Wuqing District. However, the emissions due to industrial processes should be controlled on a priority basis in Ninghe District and Binhai District, followed by Jinnan District. The reduction measures for transport emission were found to be the most influential in Beichen District, Dongli District, and the central districts and should be a priority in these districts.

CONCLUSIONS

In this study, two nested domains, with a horizontal resolution of 12 km for the inner domain, were set up with the WRF-Chem model to simulate a severe pollution episode that occurred in northeastern China during December 2015. The model's performance was then evaluated using NCDC meteorological surface observations and the air quality monitoring database released by CNEMC. Twelve emission reduction scenarios involving nine major sectors and three subsectors were simulated for Domain 2 to evaluate the effects of emission reduction measures on air quality. Based on our results, we have provided feedback and optimized emergency emission reduction plans.

Overall, the meteorological simulations by the WRF-Chem model are acceptable; however, an overestimation of the wind speed and an underestimation of the precipitation occurred for December 2015. All of the predicted $PM_{2.5}$

concentrations were also acceptable, agreeing well with the observations in the suburban districts and Binhai District, although they were relatively overestimated in the central districts and most sites in the adjoining districts, except for Huaihe Road in Beichen District.

Adverse meteorological conditions increased the PM_{2.5} concentrations by approximately 34% during the heavy haze pollution episode. Thus, the considerable influence of adverse meteorological conditions should not be neglected.

An approximate decrease of 18.9% was observed in the total PM_{2.5} concentration when an emergency plan during the red alert condition was implemented during the pollution episode. The largest contributor to the PM_{2.5} was fossil fuel combustion, followed by dust emission and industrial processes. Due to the decrease in gaseous precursors and the adverse secondary reactions during the pollution dissipation stage, mainly, emission reductions for industrial sources (including industrial processes and industrial boiler combustion), domestic combustion, and agriculture produced greater effects during this stage than the accumulation stage. According to the difference assessments, dust emission and fossil fuel combustion play major roles in the PM_{2.5} concentrations in most districts of Tianjin, but industrial processes contribute a higher proportion in the adjoining districts and Binhai District. Moreover, controlling agricultural emission is crucial in the southwestern suburban districts of Tianjin.

Several suggestions are offered in this study. First, different mitigation measures should be adopted in different districts, e.g., dust emission and industrial processes should be controlled on a priority basis in the northeastern suburban districts, and the adjoining districts and Binhai District, respectively. Second, different mitigation measures should be adopted during different pollution stages, e.g., industrial sources should be controlled on a priority basis during the dissipation stage. The present study provides preliminary results, but additional experiments with different scenarios containing heavy haze episodes are required for further analysis.

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