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Strategies towards $PM_{2.5}$ attainment for non-compliant cities in China: A case study

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ABSTRACT

The northern part of the Yangtze River Delta (YRD) region in China suffers from high concentrations of fine particular matter ($PM_{2.5}$) during the past years yet received much less attention compared to the other parts of the YRD region. In this study, we integrated observational data, control policies and strategies, and air quality simulations to develop $PM_{2.5}$ attainment demonstration by year 2030 for the city of Bengbu, which represents a typical non-compliant city in the northern YRD region. In 2018, the annual average $PM_{2.5}$ concentration in Bengbu was 51.8 μg/m^3, which was 48 % higher than the standard of 35 μg/m^3 set by the National Ambient Air Quality Standards (NAAQS). Different future emission scenarios were developed for year 2025 as mid-term and year 2030 as long-term. Integrated meteorology and air quality modeling system together with monitoring data was applied to predict the air quality under the future emission scenarios. Results show that when a conservative emission reduction ratio of 40 % was assumed for surrounding regions, the annual average $PM_{2.5}$ concentration in Bengbu could meet the target value by 2030, in which case emissions of SO_2, NOx, $PM_{2.5}$, VOCs, and NH_3 need to be reduced by 70.6 %, 43.5 %, 47.2 %, 33.4 %, and 47.5 %, respectively. $PM_{2.5}$ concentration in Bengbu is not only controlled by local emission reductions but also affected by emission reductions of surrounding regions as well as contribution from long-range transport. More attentions need to be paid to the control of VOCs emissions in the near future to avoid increase of ozone concentrations while reducing $PM_{2.5}$. Our results provide scientific support for the local government to formulate future air pollution prevention and control strategies, sub-regional joint-control among surrounding cities, as well as trans-regional joint-control between the north China and the YRD region.

1. Introduction

Over the past several decades, China has achieved remarkable success in its economic development. Along with this fast-economic growing and rapid urbanization, China is facing an environment of deteriorated air quality with frequent occurrences of heavy haze pollution during the winter (Bei et al., 2020; Feng et al., 2020; Gao et al., 2020; Miao et al., 2020; She et al., 2020a; Shen et al., 2020; Wang et al., 2019a) and increasing ozone pollution during the summer (Chen et al., 2019; Fang et al., 2020; Liu and Wang, 2020; Pu et al., 2017; Zhao et al., 2020). Significant amounts of primary air pollutants are continuously emitted by anthropogenic activities into the atmosphere and under unfavorable meteorological conditions, these primary air pollutants will react, accumulate, and spread, thereby leading to regional heavy air pollution, for example, the infamous heavy haze event occurred in January 2013 over the North China Plain (Chen et al., 2017; Han et al., 2016; Li et al., 2017; Miao et al., 2017; Yuan et al., 2015; Zhang et al., 2020). In August 2013, the China State Council released the Air

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Pollution Prevention and Control Action Plan (APPCAP), which set specific targets to reduce $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) concentrations in three key metropolitan regions (i.e. the Beijing-Tianjin-Hebei (BTH) region in northern China, the Yangtze River Delta (YRD) region in eastern China, and the Pearl River Delta (PRD) region in southern China) (Feng et al., 2019; Geng et al., 2019; Wang et al., 2019b; Wu et al., 2020; Xue et al., 2019; Zhang et al., 2018, 2019). In July 2018, the State Council issued the Three-Year Action Plan for Winning the Blue Sky Defense Battle (referred to as the "Three Year Plan'‘), which clearly states that the YRD region shall continuously perform air pollution prevention and control actions via optimizing the structures of industry, energy consumption, transportation, and land use, closely monitoring pollution controls in autumn and winter, and strengthening regional cooperation on controlling heavy air pollution (http://english.mee.gov.cn/News_service/news_release/201807/t20180713_446624.shtml, accessed on August 15, 2020, references herein). The revised version of the Atmospheric Pollution Prevention and Control Law of the People's Republic of China clearly states that "governments of non-attainment cities shall promptly formulate emission reduction plans for meeting the National Ambient Air Quality Standards (NAAQS) and carry out these plans accordingly in order to attain the standards within the time limit set by the state council or the provincial government".

The YRD region, being one of the most populated regions in China and containing some of the fastest-growing economies in recent years, has frequently suffered from heavy haze pollution (Chen et al., 2020; She et al., 2020b; Sun et al., 2019; Zhou et al., 2019). Among Shanghai and 40 other cities from the Jiangsu, Zhejiang, and Anhui Provinces in the YRD region, 33 cities (80.5 %) failed to meet the annual $PM_{2.5}$ standard set by the NAAQS in 2018. There have been many studies targeting the air pollution status in the YRD city cluster (Hu et al., 2014; Li et al., 2020b; Wang et al., 2020; Zhang et al., 2016). However, compared to the other parts of the YRD region that are more frequently studied, the northern areas in the YRD region have been experiencing the most severe air pollution yet have received much less attention. The city of Bengbu, located in the northern part of the YRD region (Fig. 1), represents a typical non-compliant city among many in the northern YRD. In 2018, annual average $PM_{2.5}$ concentration in Bengbu was 51.8 $\mu g/m^3$, exceeding the NAAQS by 48 %. In 2020, the annual $PM_{2.5}$ concentration dropped to 43.7 $\mu g/m^3$, largely attributable to the outbreak of COVID-19 and partially to the emissions reduction and favorable meteorology. Nevertheless, the attainment of $PM_{2.5}$ concentration in Bengbu remains to be a challenging and on-going task.

This study integrates observational data, control policies and strategies, and air quality simulations to develop $PM_{2.5}$ attainment demonstration for the city of Bengbu. Several steps were taken to achieve this goal. Firstly, a comprehensive review of air quality trends in Bengbu over the past few years was conducted. Secondly, a base case emission inventory was developed for 2018 and emissions under different future scenarios with various assumptions of control strategies were estimated for year 2025 (mid-term) and 2030 (long-term), respectively. Finally, an integrated meteorology and air quality model was utilized to demonstrate the reduction in annual $PM_{2.5}$ concentrations under different future scenarios. The results of this study can provide scientific support for the city government to formulate future air pollution prevention and control strategies. This study also presents a comprehensive framework that may be used to demonstrate pollution controls for other non-compliant cities in China.

2. Methodology

2.1. Model configurations

In this study, an integrated meteorology and air quality model was used to simulate air quality improvements under different emission reduction scenarios. Meteorological fields were simulated by the

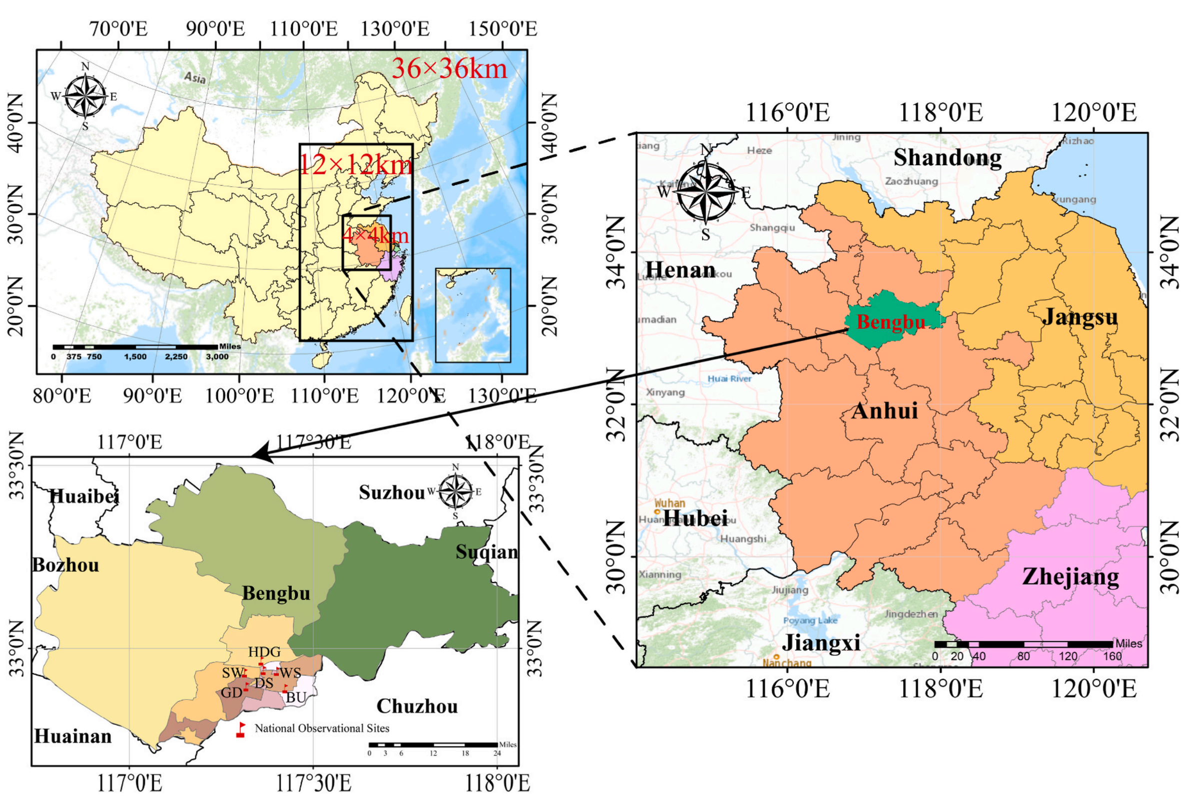

Fig. 1. Modeling domain as well as the locations of Bengbu and six national monitoring (Workers' Sanatorium (WS, latitude: 32.9369°N, longitude: 117.4016°E), Department Store (DS, 32.9393°N, 117.3651°E), Secondary Waterworks (SW, 32.9325°N, 117.3141°E), Bengbu University (BU, 32.8899°N, 117.4241°E), Huaishang District Government (HDG, 32.9655°N, 117.3592°E), Gaoxin District (GXD, 32.8951°N, 117.3183°E)).

Weather Research Forecasting (WRF) model version 3.7.1 (https://www.mmm.ucar.edu/wrf-model-general). The initial and boundary conditions for the WRF modeling were based on the National Centers for Environmental Prediction Final Operational Global Analysis data with a spatial resolution of 1 ° × 1 ° grid. The boundary conditions for WRF are updated at 6-h intervals for the outer 36 km × 36 km domain. The Yonsei University (YSU) scheme (Hong et al., 2006) was applied to parameterize the boundary layer processes; the NOAH land surface scheme (Ek et al., 2003) was used to describe the land-atmosphere interactions; the Purdue-Lin microphysics scheme (Lin et al., 1983) was chosen to reproduce the cloud and precipitation processes; and the RRTM long-wave and Goddard Short-wave radiation schemes (Chou et al., 1999; Mlawer et al., 1997) were adopted to reflect radiation.

The Comprehensive Air Quality Model with Extensions (CAMx) version 6.5 (http://www.camx.com/) was employed as the air quality model. CAMx configurations are similar to our previous study (Huang et al., 2019; Li et al., 2019a, 2019b, 2020a), which include the carbon bond 6 (CB6) as the gas phase chemical mechanism (Yarwood et al., 2010), the static two-mode coarse/fine (CF) scheme for particle size distribution, ISORROPIA (Nenes et al., 1998) for inorganic aerosol chemistry, SOAP2.1 for secondary organic aerosol (SOA) simulation, Zhang's dry deposition (Zhang et al., 2003) and a default wet deposition scheme for removal processes. The modeling domain consists of three nested grids (Fig. 1): the outer two 36 km/12 km domains cover eastern Asia and eastern China, respectively, and the inner 4 km domain covers northern Anhui Province and its surrounding regions, with the city of Bengbu located in the center of the domain. Initial and boundary conditions for the 36 km domain were generated from the Community Atmosphere Model with Chemistry (CAM-chem; https://www2.acom.ucar.edu/gcm/cam-chem; accessed on March 24, 2020). Biogenic emissions were simulated using the Model of Emissions of Gases and Aerosols from Nature (MEGAN, version 2.1, (Guenther et al., 2012) with meteorological fields generated by WRF. Anthropogenic emissions for the outer two domains were based on the Multi-Emission Inventory for China (MEIC) developed by Tsinghua University (http://www.meicmodel.org/). For the 2018 base case simulation, an YRD-specific emission inventory (Huang et al., 2011; Li et al., 2011) updated as of 2017 was applied for the 4 km domain in this study. For future scenario simulations, emission reduction ratio of 20 % and 40 % was assumed for the outer two domains for year 2025 and 2030, respectively, and emissions within the 4 km domain were replaced by one of the eight future emissions listed in Table 1; other model inputs and configurations were kept identical to the base simulation. Both the base emissions and future scenario emissions were processed into speciated, hourly, and gridded emissions using the Sparse Matrix Operator Kernel Emissions (SMOKE) model version 3.7. All simulations were conducted for February, May, August, and November, representing winter, spring, summer, and autumns, respectively. A spin-up period of five days was used for each month to reduce the effect of the initial conditions.

A base case emission inventory was first developed for the city of Bengbu for 2018 based on activity data collected from statistics reports, field surveys, and emission tests of major sources. Four future emission scenarios were developed considering future trends of population, economic development, energy consumption, and the implementation of different control technologies by 2025 and 2030. Concentrations of $PM_{2.5}$ and other criteria pollutants were simulated for one base case (2018) and 16 future scenarios (eight for 2025 and eight for 2030) with identical model configurations except anthropogenic emissions. Simulated $PM_{2.5}$ concentrations for future scenarios were then adjusted to future design values (DVF) and compared with the NAAQS standard for attainment demonstration. Further details are provided below as well as in the Supplemental Information.

Table 1
List of emission reduction scenarios.

No.	Scenario	Emissions reduction for Bengbu	Emissions reduction for surrounding cities	Emissions reduction for north China
1	Base	2018 base emissions	YRD-specific emission inventory (2017)	MEIC (2017, http://www.meicmodel.org/)
2*	BAU_A	BAU	Base emissions reduced by 20 % for 2025 and 40 % for 2030 (conservative estimate)	Base emissions reduced by 20 % for 2025 and 40 % for 2030
3	NP0_A	NP0		
4	NP1_A	NP1		
5	NP2_A	NP2		
6	BAU_B	BAU	Base emissions reduced by 40 % for 2025 and 60 % for 2030 (optimistic estimate)	
7	NP0_B	NP0		
8	NP1_B	NP1		
9	NP2_B	NP2		

2.2. Development of future emission scenarios

A base emission inventory was developed for the city of Bengbu for year 2018 including nine anthropogenic emission categories: industry (industrial combustion and industrial processes), on-road, non-road, dust, solvent use, residential, storage and transport, agriculture, and waste treatment. The development of base emission inventory followed the national technical guidelines for emission inventory compilation for different sources. Activity data and emission factors were collected from statistics reports, local surveys, field investigations, and emission tests of key sources when possible. More details of the base emission inventory are presented in Table S1.

Four future emission scenarios were developed for the city of Bengbu by year 2025 and year 2030, respectively, considering the requirements for air pollution prevention stated in the 13th Five Year Plan at the city, provincial, and national levels, individual plans for industry, energy, and land use issued by local bureaus, as well as future trends of population, economic development, energy consumption, and on-road vehicles (Table S2). The business-as-usual (BAU) scenario was constructed based on the assumptions that the development of power usage, industry, transportation, and other sectors will maintain current trajectories, existing control policies and execution efforts will continue, and new energy conservation policies will not be introduced. The main features of the BAU scenario include: the economic growth is maintained at a high level, industrial activities and energy consumption continue to grow at their existing speeds, and the number of vehicles will continue to increase. The other three future emission scenarios were developed on top of the BAU scenario with different levels of new control policies (NP): baseline control (NP0), enhanced control (NP1), and maximum control (NP2). NP0 represents a structural adjustment scenario, which assumes that a sustainable energy development strategy will be adopted in the future, including changing production methods, adjusting the energy and industrial structures, improving the efficiency of energy utilization, and full implementation of policies formulated by the government. Under this scenario, no new emission reduction policies are introduced. The main features of this scenario include a slowing of economic growth, optimization of industrial and transportation structures, enhanced control over total energy and coal consumption, a controlled growth rate of on-road vehicles, and further reductions in the use of pesticides and chemical fertilizers. NP1 extends upon NP0 and assumes that new emission control policies will be issued continuously in the future. This scenario represents the best estimate of future policy trends, and main features include further improvements of end-of-pipe treatment of key industries such as electric generation, industrial boilers, glass, cement, chemicals, and packaging and printing; additionally, stricter vehicle emission standards, an accelerated elimination of old vehicles, effective control of off-road machinery, enhanced management of dust sources, and promotion of large-scale and intensive agricultural development will occur. NP2 assumes the maximum application of technically feasible emission reduction technologies based upon NP0. This scenario represents the maximum emission reduction that can be realized via various pollution control measures and exercising the highest level of control on emissions from power, industry, residential, transportation, and other sectors. Table S3 shows the detailed assumptions for power plants, industrial boilers, key industries (e.g., production of glass, cement, ceramic, tiles, petrochemical, etc.), automobiles, dust, cooking, and agricultural activities for each of the NP scenarios. Activity data for the BAU and NP scenarios are determined by trend extrapolation based on various published planning documents (Table S2). In addition to future emission scenarios for the city of Bengbu, two emission reduction scenarios were developed for the surrounding cities (Scenario A and Scenario B) based on the national and regional goals for $PM_{2.5}$ reduction in the YRD region. Scenario A represents a relatively conservative estimate with the assumption that the emission reductions of surrounding cities will be approximately 20 % for 2025 and 40 % for 2030, and Scenario B represents a relatively optimistic estimate with the surrounding emission reduction ratio set to 40 % for 2025 and 60 % for 2030. This leads to sixteen future emission scenarios (eight for 2025 and eight for 2030) used in this study (Table 1).

2.3. Attainment demonstration

In this study, the relative response factor (RRF) concept (U.S.EPA, 2007) was adopted to calculate future year concentrations (DVF) based on model results and observations. The RRF is simply a ratio of a future year simulated concentration to a base year simulated concentration for a target pollutant (e.g., O_3, $PM_{2.5}$) (Odman et al., 2020). Future year concentrations are estimated by multiplying the RRF by the base year design value (DVC), which is the observed concentration at the national monitoring sites for 2018. The calculation of RRF and DVF is illustrated as follows:

$$\text{Relative response factor (RRF)} = C_f / C_b \tag{1}$$

$$\text{DVF} = \text{DVC} \times \text{RRF}. \tag{2}$$

where C_f and C_b are simulated future year and base year concentrations, respectively. Because simulations were only conducted for four months in this study, annual concentrations were calculated by projecting four-month averaged concentrations to the annual concentrations based on the ratio of the 12-month average to 4-month average of observations (Yu et al., 2019). Ozone concentrations were highest during summer and autumn; thus, the ratio of the annual 90th maximum daily 8-h ozone concentrations (MDA8 O_3) to average monthly MDA8 O_3 for August (summer) and October (autumn) was used to calculate the annual 90th MDA8 O_3 concentrations. The adjusted annual $PM_{2.5}$ concentrations were compared with the NAAQS standard to address attainment.

3. Results and discussions

3.1. Air quality status for city of Bengbu

Six national monitoring sites are located in the city of Bengbu, with one for each urban district (Fig. 1). Fig. 2 shows the observed annual average concentrations of criteria pollutants in Bengbu during 2013–2019 (values are averaged over the six monitoring sites). The concentrations of annual PM_{10} and SO_2 exhibited a decreasing trend during 2013–2018, with reductions of 21.6 % and 39.7 %, respectively. Remarkable improvements have thus been achieved in the prevention and control of air pollution, especially regarding coal-smoke pollution. Beginning in 2015, the city of Bengbu began monitoring six conventional air pollutants (i.e., PM_{10}, $PM_{2.5}$, CO, NO_2, SO_2, and O_3), and the concentrations of annual CO and $PM_{2.5}$ exhibited a decreasing trend during 2015–2018, with reductions of 25.0 % and 14.8 %, respectively. In 2018, the annual average $PM_{2.5}$ concentration in Bengbu was 51.8 μg/m^3, which was 48.0 % higher than the goal set by NAAQS. NO_2 concentrations remained relatively unchanged, whereas the 90th daily maximum 8-h O_3 concentration increased from 118 μg/m^3 in 2015 to

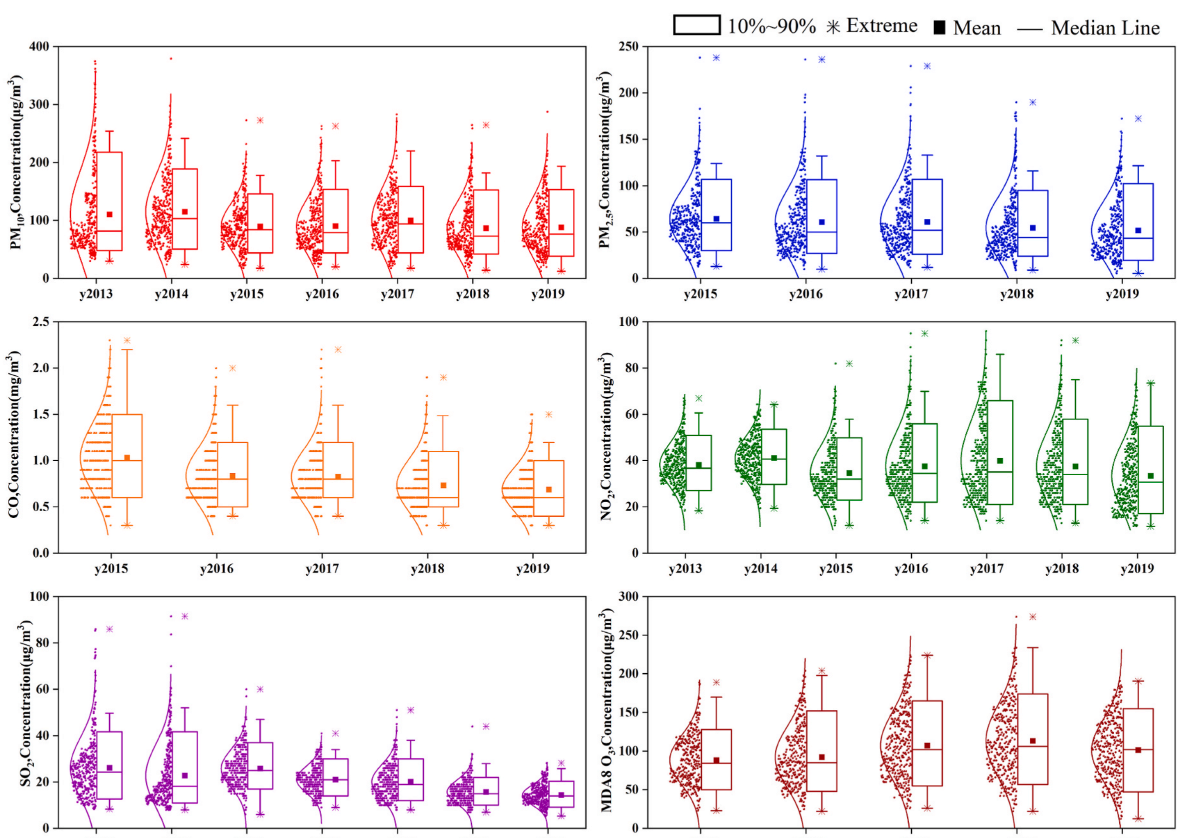

Fig. 2. Annual average concentrations of criteria pollutants in Bengbu during 2013–2019.

162 μg/m^3 in 2018, representing a relative increase by 37.3 %. The averaged MDA8 concentration during ozone season (May–October) increased from 116.4 μg/m^3 in 2015 to 143.4 μg/m^3 in 2018, suggesting worsening ozone pollution in the city of Bengbu. Fig. 3 shows the spatial distribution of annual average $PM_{2.5}$ concentrations throughout the YRD region in 2018. Relatively high concentrations were observed in the north Anhui (where Bengbu is located) and north Jiangsu Provinces. Among the 41 cities of the YRD region, the average annual $PM_{2.5}$ and PM_{10} concentrations of Bengbu in 2018 ranked 33rd and 34rd, respectively. The annual concentration of NO_2 in Bengbu was 35 μg/m^3, which ranked 27th out of the 41 cities. This reveals that particulate matter pollution was most serious in 2018 in the northwestern part of the YRD region and it is necessary to strengthen the prevention and control of particulate matter pollution in this area.

3.2. Emissions estimation

3.2.1. Base emission inventory

The annual anthropogenic emissions for the city of Bengbu in 2018 included 8.5 kt (kilotons) of SO_2, 35.4 kt of NOx, 69.4 kt of PM_{10}, 19.7 kt of $PM_{2.5}$, 25.1 kt of VOCs, and 63.3 kt of NH_3 (see details in Table S3). Industrial stationary combustion was the dominant SO_2 source, accounting for 91.5 %. Automobiles contributed the most (47.3 %) to NO_x emissions, followed by off-road machinery (29.4 %) and industrial combustion (18 %). Dust was the dominant source for $PM_{2.5}$ and PM_{10}, accounting for 50.2 % and 74.8 %, respectively. Ammonia emissions mainly came from livestock (69.3 %) and fertilizer applications (24.6 %), whereas VOCs emissions mainly resulted from motor vehicles (28.8 %) and industrial processes (15.7 %).

3.2.2. Emissions under different future scenarios

Emissions under different future scenarios were estimated for both year 2025 as mid-term and year 2030 as long-term. Table S4-S7 shows the emission changes under different future scenarios relative to the base emissions by detailed sectors. Under the natural growth scenario (BAU), there will be 18,344 tons of SO_2 (relative change: 25.6 %), 49,606 tons of NOx (31.5 %), 22,449 tons of $PM_{2.5}$ (8.1 %), 25,145 tons of VOCs (0.1 %), 65,544 tons of PM_{10} (−4.3 %), and 52,782 tons of NH_3 (−16.6 %) in Bengbu by 2025. Corresponding values by 2030 are 20,068 tons of SO_2 (37.4 %), 59,423 tons of NOx (57.5 %), 22,969 tons of $PM_{2.5}$ (10.6 %), 27,180 tons of VOCs (8.2 %), 64,841 tons of PM_{10} (−5.3 %), and 38,211 tons of NH_3 (−39.6 %). Increased emissions under this scenario are mainly caused by the growth of industrial products, increased number of on-road vehicles, and more construction areas resulting from urban expansion. Emissions from road dust, the use of architectural coatings, and livestock and poultry farming in agricultural sources will exhibit decreasing trends owing to improved management; the use of pesticides and fertilizers will also decrease annually.

Under the baseline control scenario (NP0), emissions of all pollutants in Bengbu will decrease in 2025 and 2030 (except for NOx in 2025), with percentage reductions of −10 % to −48 % by 2030 (Table S5). Compared with the BAU scenario, emissions from stationary combustion sources, on-road vehicles, and dust emissions decrease substantially. SO_2 and PM emissions from stationary combustion sources change from an increasing trend in the BAU scenario to a decreasing trend in the NP0 scenario owing to the adjustment of the energy consumption structure (for example, the "coal to gas/electricity" policy). Except for SO_2 and NH_3, pollutants emitted by on-road vehicles will decrease substantially (−15 % to −70 % by 2030) in NP0 compared with the base emissions. Dust control under the NP0 scenario leads to an emission reduction around 10 % for construction dust and 60 % for road dust by 2030

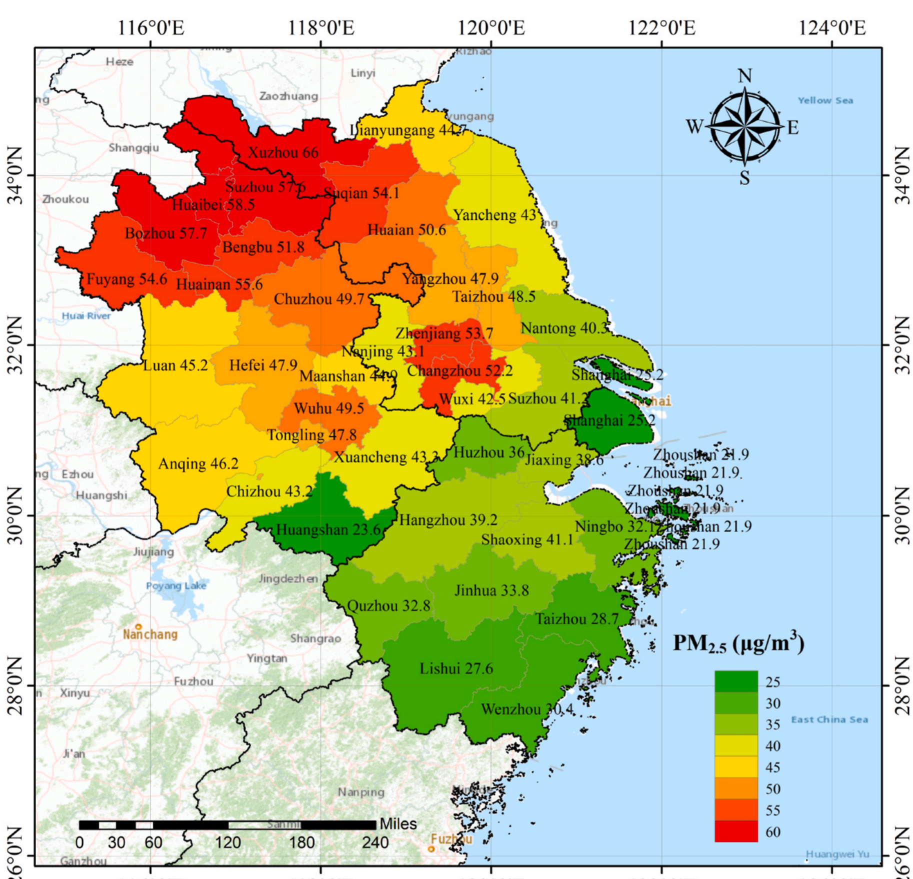

Fig. 3. Spatial distribution of annual average $PM_{2.5}$ concentrations in the YRD region in 2018.

compared to the base scenario. For the enhanced control scenario (NP1), emissions of all pollutants are further reduced with reduction percentages over 30 % by 2030 (Table S6). Emissions from industrial processes will decrease for all pollutants (except NH_3), with NOx and VOCs emissions decreasing by more than 40 % by 2030. SO_2 emissions from industrial combustion sources will reduce by more than 65 % by 2025 and 70 % by 2030 and because the total SO_2 emissions are dominantly contributed by industrial combustion, the overall SO_2 emissions will be reduced by 65 % by 2025 and 70 % by 2030. Emissions from on-road vehicles, off-road machineries, and dust will be further reduced compared with NP0, whereas emissions from agriculture and solvent use are unchanged from NP0. For the maximum control scenario (NP2), emissions will be reduced by more than 40 % for all pollutants by 2030 (Table S7); $PM_{2.5}$ emissions will decrease by over 50 %. Only VOCs and NH_3 emissions from industrial combustion sources are higher than base emissions. Compared with NP0 and NP1 scenarios where no controls are applied for asphalt use, VOCs emissions from asphalt use will be 30 % lower. Emissions from off-road machinery, construction dust, on-road vehicles, industrial combustion sources, and industrial processes will be further reduced from the NP1 scenario.

Fig. 4 shows the emissions for the four future scenarios by 2025 and 2030 and the relative changes with respect to the 2018 base level. Except for the increase in the total emissions of SO_2, NOx, VOCs, and $PM_{2.5}$ in the BAU scenario relative to the baseline scenario, all pollutants in the other scenarios exhibit a decreasing trend, with the largest proportional decrease from BAU to NP0 and a gradual decrease from NP0 to NP2 in 2030. The emissions of NH_3 remain essentially unchanged in the NP0, NP1, and NP2 scenarios in 2025 and 2030.

3.3. Future air quality trends

3.3.1. Base case model evaluation

Fig. 5 shows the spatial plots of simulated monthly averaged concentrations of $PM_{2.5}$, SO_2, NO_2, and O_3 for the 4 km domain with overlay of observed concentrations at selected monitoring stations for Bengbu and surrounding cities for each modeling month. Overall, the model is able to capture the spatial and seasonal changes in $PM_{2.5}$, SO_2, and NO_2 concentrations with over-estimations of O_3 concentrations. The concentrations of $PM_{2.5}$, SO_2, and NO_2 show a clear pattern of highs in autumn (November) and winter (February) and lows in spring (May) and summer (August). O_3 concentrations are highest in spring and lowest in autumn and winter. From a spatial perspective, the highest values of SO_2, NO_2, and $PM_{2.5}$ are mainly concentrated in urban areas, which are related to urban population, motor vehicle density, and pollutant emissions, while O_3 concentrations are usually higher in suburban areas than in urban areas due to NO titration.

Fig. S1 shows the time series of simulated and observed hourly $PM_{2.5}$ concentrations for six cities in northern Anhui Province. We further calculated the mean bias (MB), normalized mean bias (NMB), and index of agreement (IOA) based on pairs of hourly observed and simulated $PM_{2.5}$ concentrations by city and by month. In general, the model captured hourly variations in $PM_{2.5}$ concentrations. Because the most updated emission inventory developed in this study was used for Bengbu, the model performed best for Bengbu, with an NMB between −28 % and −5% and an IOA between 0.52 and 0.79 (Table 2). The evaluation results for Huainan and Bozhou were relatively satisfactory, with IOA values above 0.5 and NMB within 30 %. The model performed the least effectively for Fuyang and Suzhou, where spikes of simulated hourly $PM_{2.5}$ concentration were present (Fig. S1). This could be related to the too shallow planetary boundary layer (PBL) height simulated by WRF. Various factors, including inaccurate land cover data, the choice of different PBL schemes could affect the simulated PBL height (Hong et al., 2010) caused by uncertainties associated with the emission inventory. Seasonally, the model performed better for fall and winter than for spring and summer (Table S8).

We further validated the simulated $PM_{2.5}$ results at six national monitoring sites located within the urban area of Bengbu (results of MB, NMB, and IOA shown in Fig. 6). The model under-estimates $PM_{2.5}$ concentrations in February and May but shows overestimations in the other two months. NMB values at all six sites are within 30 %, and for some sites, NMB values are within 5 %; the average NMB across six sites is less than 10 %. The IOA values for all sites and months are above 0.5, with the highest value of 0.82. These results suggest that the model successfully simulated $PM_{2.5}$ concentrations for Bengbu, which ensures the reliability of the following analysis.

3.3.2. Predicted air quality under future emission scenarios

Table 3 shows the simulated concentrations for different air pollutants under different future emission scenarios by 2025 and 2030. Under the BAU scenarios where emissions of SO_2, NOx and $PM_{2.5}$ are estimated to increase due to the growth of industrial products, increased number of on-road vehicles, and increasing construction areas as a result of urban expansion, $PM_{2.5}$ concentration is estimated to be reduced by 10–15 % compared to year 2018, mostly attributable to the emission reductions

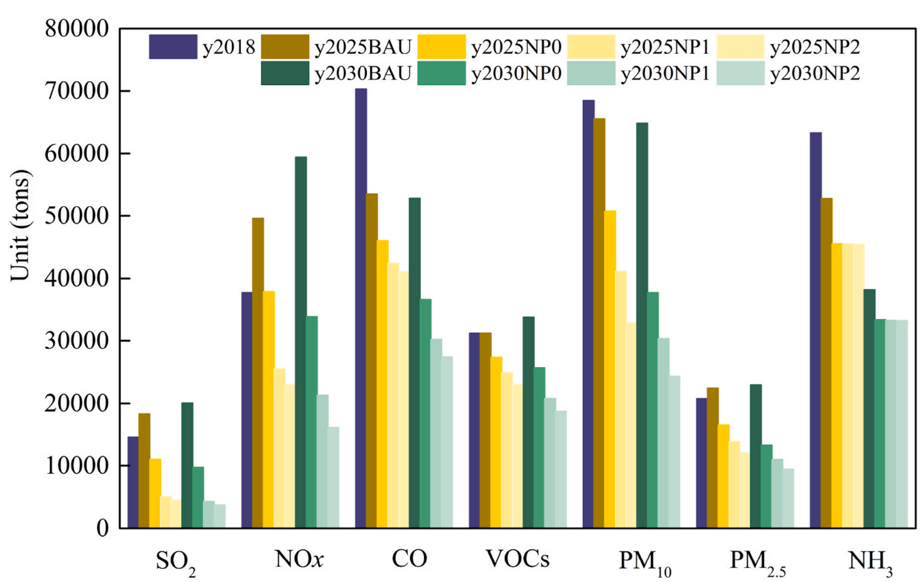

Fig. 4. Emissions for year 2018 and four future scenarios in 2025 and 2030 (unit: tons).

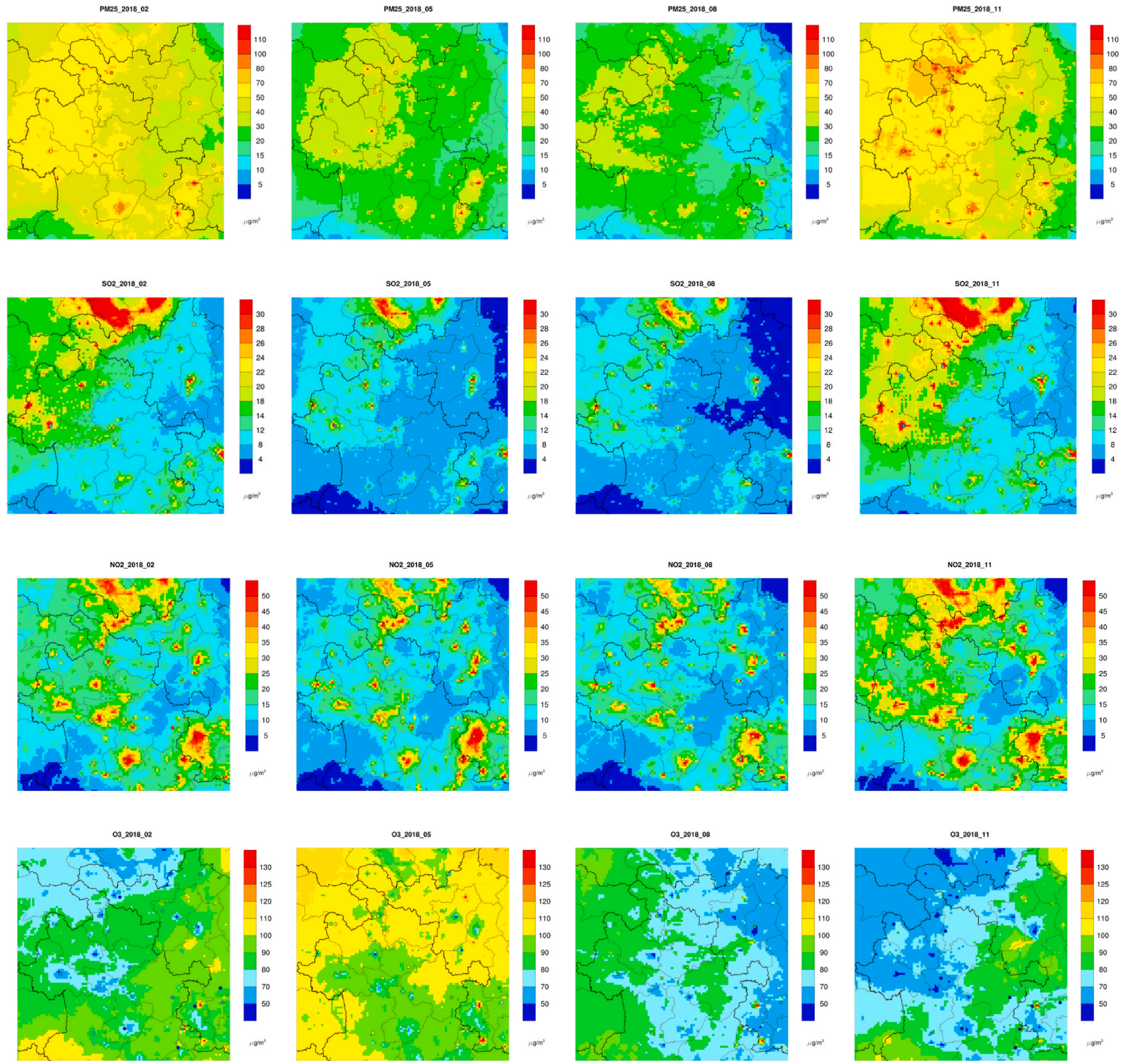

Fig. 5. Spatial distributions of observed and simulated monthly average $PM_{2.5}$ (first row), SO_2 (second row), NO_2 (third row) and O_3 (fourth row) concentrations for the 4 km domain for February (first column), May (second column), August (third column), and November (fourth column). Dots within the map indicate observational data.

Table 2
Parameter evaluation results of the CAMx simulation effect on six cities in northern Anhui Province (by city).

city	MB (μg/m^3)	NMB	IOA
Bengbu	−17.2 ~ −1.6	−28 % ~ −5%	0.52–0.79
Huainan	−25.1 ~ −1.7	−29 % ~ 30 %	0.57–0.80
Huaibei	−14.8–17.2	−15 % ~ 43 %	0.41–0.76
Fuyang	10.7–29.1	12 % ~ 160 %	0.33–0.74
Suzhou	7.0–34.4	10 % ~ 42 %	0.26–0.63
Bozhou	−29.3–6.3	−32 % – 20 %	0.47–0.78

of surrounding cities and lower contribution of long range transport. As the emission reduction goes from BAU scenario to more controlled NP scenario, the concentration of $PM_{2.5}$ becomes lower as expected. However, under the most stringent emission control strategies in Bengbu and an optimistic estimate of emission reductions for surrounding cities (i.e. 2025NP2_B), the annual average $PM_{2.5}$ concentration for the city of Bengbu is 35.8 μg/m^3 by 2025, representing a reduction by 30.8 %, but is still slightly above the national standard of 35 μg/m^3. Optimistic emissions reduction for surrounding cities leads to lower $PM_{2.5}$ concentrations by 15.3 %~30.8 % compared to conservative estimate of emission reductions, which illustrates the importance of regional joint prevention and control. For PM_{10}, the simulated annual average concentration could meet the national standard of 70 μg/m^3 under NP0 scenario by 2025. The concentration of NO_2, SO_2 and CO is already

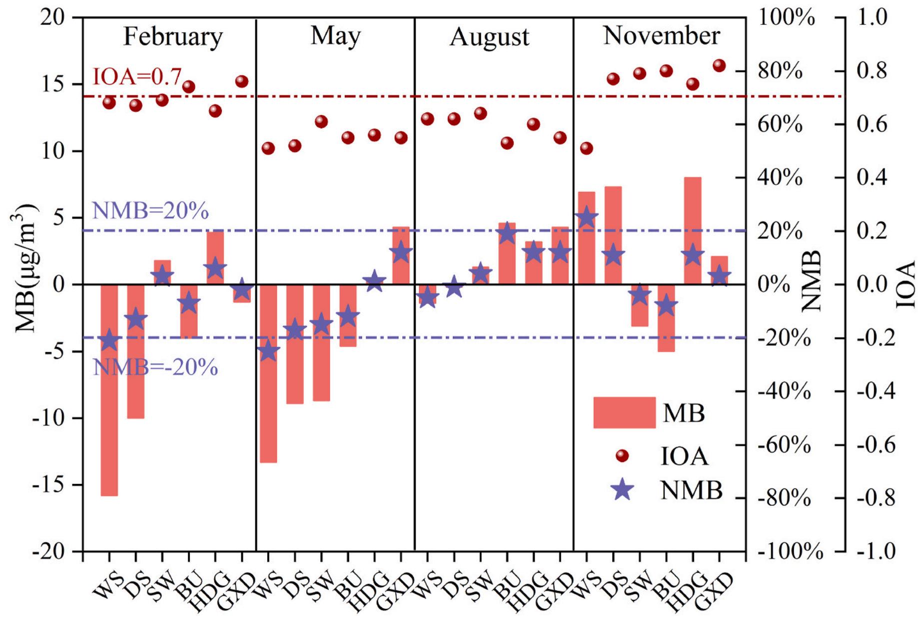

Fig. 6. Simulated statistical parameter results for $PM_{2.5}$ at six national observational sites in Bengbu (dashed lines represent the criteria benchmarks proposed by Huang et al. (2021a)).

below the standard and is further reduced under scenarios with more reductions of emissions. In contrast, the 90th MDA8 ozone concentration shows an opposite trend going from BAU scenarios to NP scenarios. For example, under NP1 and NP2 scenarios, the predicted 90th MDA8 ozone concentration would exceed the national standard of 160 μg/m^3. This illustrates the nonlinear response of ozone concentrations to changes in precursor emissions. Inappropriate ratio of reductions in the NOx and VOCs emissions could lead to higher ozone concentration. For instance, the substantial reductions of NOx emissions during COVID-19 have been reported to cause increased ozone concentration in China (Huang et al., 2021b; Li et al., 2020a; Shi and Brasseur, 2020). More stringent VOCs reductions would be required in order to reduce $PM_{2.5}$ and ozone concentrations simultaneously. As ozone is merging as another key pollutant in many cities across China, it is expected that future policies (e.g. the forthcoming 14th Five Year Plan) would emphasizes more on the reductions of VOCs emissions in urban areas, which are generally considered as VOCs-limited regions. In addition, significant efforts need to be spent on identifying the sources and subsequent controls of key VOCs species that have high ozone formation potential, for example, olefins, aromatics, and oxygenated VOCs (OVOCs).

By year 2030, by which the annual average $PM_{2.5}$ concentration is required to attain the national standard, the natural growth scenario (BAU_A) results in an annual averaged $PM_{2.5}$ concentration of 42.5 μg/m^3. Compared with 2018, the annual $PM_{2.5}$ concentration in the BAU_A scenario decreases by 18 % but is still much higher than the target concentration (i.e. 35 μg/m^3). The annual $PM_{2.5}$ concentration further decreases to 35.2 μg/m^3 (a 32 % reduction compared to 2018) when structural adjustments are considered (i.e., NP0_A scenario). When future new emission control strategies are also considered (i.e., NP1_A), the predicted annual $PM_{2.5}$ concentration is 33.1 μg/m^3 by 2030, which is able to meet the standard. Under this scenario, emissions of $PM_{2.5}$, SO_2, NOx, and VOCs are estimated to be reduced by 47.2 %, 70.6 %, 43.5 %, and 33.4 %, respectively (Table S6). Again, the intensity of emission reductions in the surrounding area will greatly affect the $PM_{2.5}$ compliance status for the city of Bengbu. When a more optimistic emission reduction ratio (60 %) is assumed for surrounding regions, the annual average $PM_{2.5}$ concentration of $PM_{2.5}$ under the structural adjustment scenario (i.e. NP0_B) is 32.5 μg/m^3, which is able to meet the target concentration. Emissions of $PM_{2.5}$, SO_2, NOx, and VOCs will need to be reduced by 36.2 %, 33.4 %, 10.3 %, and 17.7 %, respectively, under this scenario (Table S5). Therefore, the $PM_{2.5}$ compliance status by 2030 is affected by both the local emission reductions in Bengbu as well as surrounding regions. Long-range transport especially from north China in winter is also of substantial importance for $PM_{2.5}$ attainment in Bengbu. We did additional simulations where the emissions outside the 4 km domain were kept constant, which represents unchanged contribution of long-range transport under future scenarios from the base simulation. In this situation, the predicted $PM_{2.5}$ concentration would be higher by 5.8 %~11.0 % compared to scenarios with reduced boundary contribution. With conservative estimates of surrounding emissions, maximum emission reductions (NP2_A) would be needed in order to achieve $PM_{2.5}$ attainment by 2030; with optimistic estimate of surrounding emissions in the future, the annual average concentration of $PM_{2.5}$ in Bengbu could achieve the target under NP1 scenario, which is shown in Table S9.

There are several policy implications based on the results above. First, continuous and substantial reductions of local emissions are essential for the city of Bengbu to attain the national $PM_{2.5}$ standard by year 2030. It is shown that the baseline control measures (BAU) are not enough to cause sufficient emission reductions; at least enhanced control measures (NP1) will be needed, which include more stringent emission standards for various industrial sectors (e.g. manufacturing of glass, cement, petrochemical products, painting and printing) and stricter management of non-industrial sources. Second, regional joint prevention and control, including sub-regional joint-control among surrounding cities as well as trans-regional joint-control between north China and the YRD region is also important. Yang et al. (2021) found that the control of primary particle emissions are effective to reduce $PM_{2.5}$ concentration at local and nearby regions whereas emission controls of gaseous precursors in advance are beneficial at regional scale (within 500 km). Last, more attention should be paid to simultaneous control of $PM_{2.5}$ and ozone concentrations. The control of VOCs emissions were not much stressed in earlier action plans and unbalanced reductions in NOx and VOCs emissions could lead to higher ozone concentration. Control measures with respect to large VOCs sources, for example, petrochemical manufacturing, industrial paintings, and gasoline vehicles, should be emphasized more.

Table 3
Concentration of pollutants (μg/m^3; CO: mg/m^3) and proportion of improvement in different scenarios (ozone concentration is 90th daily maximum 8-h average).

Scenarios	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_3	CO
Baseline Scenario	51.8	81.0	15.0	35.0	162.0	0.73
2025BAU_A	46.6 (−10.1 %)	74.5 (−8.0 %)	13.8 (−7.9 %)	33.4 (−11.0 %)	158.6 (−2.1 %)	0.60 (−18.5 %)
2025NP0_A	40.4 (−22.0 %)	63.6 (−21.4 %)	10.7 (−29.0 %)	27.4 (−26.9 %)	159.5 (−1.5 %)	0.59 (−19.8 %)
2025NP1_A	38.0 (−26.6 %)	57.2 (−29.3 %)	8.6 (−42.9 %)	21.6 (-42.5 %)	161.6 (−0.3 %)	0.58 (−20.8 %)
2025NP2_A	36.3 (−29.9 %)	49.7 (−38.6 %)	8.4 (−43.9 %)	21.0 (−44.1 %)	161.7 (−0.2 %)	0.58 (−20.8 %)
2025BAU_B	43.8 (−15.3 %)	71.8 (−11.4 %)	13.1 (−12.8 %)	31.9 (−15.0 %)	157.4 (−2.8 %)	0.59 (−19.6 %)
2025NP0_B	39.9 (−23.0 %)	62.7 (−22.6 %)	10.7 (−29.0 %)	27.4 (−26.9 %)	159.5 (−1.5 %)	0.59 (−19.8 %)
2025NP1_B	37.5 (−27.5 %)	56.3 (−30.5 %)	8.6 (−42.9 %)	21.6 (−42.4 %)	161.5 (−0.3 %)	0.58 (−20.8 %)
2025NP2_B	35.8 (−30.8 %)	48.8 (−39.8 %)	8.4 (−43.9 %)	21.0 (−44.1 %)	161.7 (−0.2 %)	0.58 (−20.8 %)
2030BAU_A	42.5 (−17.9 %)	71.3 (−11.9 %)	13.3 (−11.5 %)	33.0 (−5.7 %)	152.0 (−6.2 %)	0.56 (−23.7 %)
2030NP0_A	35.2 (−32.1 %)	54.5 (−32.7 %)	9.9 (−34.1 %)	25.4 (−27.4 %)	155.5 (−4.0 %)	0.56 (−24.1 %)
2030NP1_A	33.1 (−36.1 %)	49.3 (−39.2 %)	7.9 (−47.1 %)	17.8 (−49.0 %)	158.0 (−2.5 %)	0.55 (−25.4 %)
2030NP2_A	31.6 (−38.9 %)	42.8 (−47.1 %)	7.7 (−48.8 %)	15.2 (−56.6 %)	158.8 (−2.0 %)	0.54 (−26.1 %)
2030BAU_B	39.3 (−24.1 %)	68.8 (−15.1 %)	12.6 (−16.2 %)	24.1 (-31.1 %)	151.2 (−6.7 %)	0.55 (−24.3 %)
2030NP0_B	32.5 (−37.3 %)	52.0 (−35.8 %)	9.2 (−38.8 %)	16.6 (−52.7 %)	154.6 (−4.6 %)	0.55 (−24.7 %)
2030NP1_B	30.4 (−41.3 %)	46.7 (−42.3 %)	7.2 (−51.8 %)	16.5 (−53.0 %)	157.0 (−3.1 %)	0.54 (−26.0 %)
2030NP2_B	28.9 (−44.2 %)	40.3 (−50.3 %)	7.0 (−53.5 %)	13.8 (−60.5 %)	157.8 (−2.6 %)	0.54 (−26.7 %)
Target value	35	70	60	40	160	4

3.4. Uncertainty analysis

Results obtained in this study are associated with uncertainties from several aspects. First of all, our simulations were performed using meteorological conditions simulated for year 2018 as the representative base year. Changes in future weather conditions would certainly affect future pollutant concentrations. For example, simulations based on the WRF with Chemistry module (WRF/Chem) predict increases of solar radiation, 2-m temperature and wind speed over most of the YRD region by 2050 under the midline future climate scenario from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Gao et al., 2019); absolute humidity and precipitation will increase in the northern YRD but the planetary boundary layer height is predicted to decrease. In a broader sense, previous studies have reported an increasing trend of regional stagnation over East Asia during past several decades (Lee et al., 2020) as well as in future scenarios (Nguyen et al., 2019), which is believed to increase the summertime surface ozone concentration but have more complicated and less certain effects on PM concentration (Fu and Tian, 2019; Jacob and Winner, 2009; Schnell et al., 2016). Secondly, the estimation of emission reductions associated with certain policies is associated with large uncertainties, especially for residential sectors and VOCs and NH_3 emissions from area sources. There is a certain degree of uncertainties in assessing the reduction effects of various pollution control measures. Uncertainties in this study also come from the assumption of the emission reduction ratios for cities surrounding our target region as well as for long-range transport from north China. Our results show that regional emission reduction is crucial for $PM_{2.5}$ compliance in Bengbu, which emphasizes the importance of regional joint prevention and control.

Our predictions of mid- and long-term social and economic development in Bengbu are based on relavent planning documents and trend forecasts. However, with rapid changes in the national economic environment and the environmental protection situation in China in recent years, the pre-requisites for the original forecast could change in the coming years. In addition, with the adjustment of national and local development policies in the future, the mid- and long-term social development trends may also need to be modified. Consequently, the results of the assessment of emission reductions and air quality improvements will need to be changed accordingly. Therefore, follow-up evaluation studies should be performed on a regular basis.

4. Conclusions

The northern part of the YRD region suffers from high $PM_{2.5}$ concentrations during past years and the city of Bengbu represents a typical non-compliant city that faces big challenges of $PM_{2.5}$ attainment. Although the $PM_{2.5}$ concentration for Bengbu has decreased substantially (by 21.6 % from 2013 to 2018), the annual average $PM_{2.5}$ concentration in 2018 was still 48 % higher than the goal set by NAAQS. This study presents a comprehensive framework for demonstration of future $PM_{2.5}$ attainment by integrating observational data, future control policies and strategies, and air quality simulations. Based on our results, with an optimistic estimate of surrounding emission reductions, the annual average $PM_{2.5}$ concentration of Bengbu could meet the national standard by 2030 with emission reductions of SO_2 by 33.4 %, NOx by 10.3 %, $PM_{2.5}$ by 36.2 %, VOCs by 17.7 %, and NH_3 by 47.3 %. This represents a structural adjustment scenario, including changing production methods, adjusting the energy and industrial structures, improving the efficiency of energy utilization, and full implementation of policies formulated by the government. With relatively conservative reductions of surrounding emissions, emissions of the corresponding pollutants need to be reduced by 70.6 %, 43.5 %, 47.2 %, 33.4 %, and 47.5 %, respectively. This would require improvements of end-of-pipe treatment of key industries such as electric generation, industrial boilers, glass production, stricter vehicle emission standards, accelerated elimination of old vehicles, enhanced management of dust sources, and promotion of large-scale and intensive agricultural development. These results emphasize the importance of local emission reductions as well as sub-regional and trans-regional air pollution prevention and control.

Credit author statement

Ling Huang, Qing Li: Manuscript writing, Data collection and data analysis, Air quality modeling. Jian Xu, Lishu Shi, Liang Li, Qian Wang, Yangjun Wang, Chaojun Ge, Qiang Yang, Guozhu Zhou: Data collection and data analysis. H. Zhang, S. Zhu: Discussion. L. Li: Conceptualization, Methodology, Writing-Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.113529.

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