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Thermal Power Industry Emissions and Their Contribution to Air Quality on the Fen-Wei Plain

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Abstract: China has imposed an ultra-low emissions (ULE) standards policy regarding the emission concentrations of the thermal power industry, and the region of the Fen-Wei Plain (China), which is an important area regarding blue-sky protection, is in urgent need of accelerating the transformation of its thermal power units to conform with China's ULE standards. Based on China's high-resolution thermal power industry emission inventory, this study used the Comprehensive Air Quality Model with extensions (CAMx) to examine emissions from the thermal power industry and the associated impacts on the atmospheric environment of the Fen-Wei Plain. (1) Spatially, the highest emissions and the greatest air quality contributions were concentrated in the Shanxi and Henan areas, which are regions that have considerable power generation capacity. (2) In terms of species, NO_x represented the largest air quality contribution and registered the smallest reduction. (3) Temporally, emission sources presented the greatest contributions in summer. (4) In terms of policy evaluation, implementation of ULE standards resulted in the reduction of the contribution of thermal power industry emissions to air quality by 56.82%, 27.44%, and 44.55% for SO_2, NO_x, and $PM_{2.5}$, respectively. The results reflect the current levels of pollution on the Fen-Wei Plain attributable to the thermal power industry and provide insight in relation to decision-making processes regarding regional air quality management.

Keywords: thermal power industry; Fen-Wei Plain; air quality; CAMx

1. Introduction

In recent years, China's power system has been dominated by thermal power generation (total installed capacity in 2018: 1.14×10^9 kW). Between 2016 and 2018, China's thermal power plants generated 70.4% of the country's electricity [1], and the associated SO_2, NO_x, and particulate matter (PM) emissions accounted for 27–28%, 24–30%, and 8–11% of China's total anthropogenic emissions, respectively [1,2]. Coal-fired power plants are a major source of atmospheric emissions in China. Therefore, control of thermal power

plants is very important regarding improvement of the quality of the atmospheric environment.

In 2014, China's central government approved the transfer of control of thermal power plants to the local government [3]. Consequently, to increase gross domestic product (GDP), local governments approved the construction of a large number [4] of thermal power plants. In the following years, the installed capacity of thermal and power generation increased. In 2015, the installed capacity of the thermal power industry in China was 9.90×10^8 kW [3], and in 2018, it was 1.14×10^9 kW [5]. From an environmental perspective, the State Council proposed that the thermal power industry should achieve complete transformation to meet the ultra-low emissions (ULE) standards (35, 50, and 10 mg/m^3 of SO_2, NO_X, and PM at standard oxygen levels, respectively) by 2020 [5,6].

The Fen-Wei Plain is considered one of the most polluted areas in China. From 2010 to 2017, the concentration load of $PM_{2.5}$ and SO_2 in the atmosphere remained high, and haze pollution occurred frequently in both autumn and winter [7–9]. Thus, the Fen-Wei Plain has been included as an important region in the battle for blue-sky preservation. The thermal power industry is one of the major industries of the Fen-Wei Plain region, and its transformation to meet ULE standards has resulted in substantial reductions of associated emissions. However, the proportion of upgraded coal-burning power plants to achieve ultra-low emissions of the thermal power industry on the Fen-Wei Plain is lower than that of both the "2 + 26" cities (refers to the "2 + 26" cities in Beijing-Tianjin-Hebei and its surroundings, "2" refers to Beijing and Tianjin, "26" refers to Shijiazhuang, Tangshan, Langfang, Baoding, Cangzhou, Hengshui, Xingtai, and Handan in Hebei Province, Taiyuan, Yangquan, Changzhi, and Jincheng in Shanxi Province, Jinan, Zibo, Jining, Dezhou, Liaocheng, Binzhou, and Heze in Shandong Province, Zhengzhou, Kaifeng, Anyang, Hebi, Xinxiang, Jiaozuo, and Puyang in Henan Province) and the Yangtze River Delta region [10]. Therefore, it is very important to study the impact of the ultra-low transformation of the thermal power plan and the associated air pollutant emissions on the quality of the atmospheric environment of the Fen-Wei Plain. To address these problems, it is essential to examine the contribution to air quality of the emissions of the thermal power industry on the Fen-Wei Plain.

Many previous studies have investigated the contribution to the atmospheric environment of emissions from the thermal power industry on national, regional, and city scales. For example, on the national scale, the thermal power industry emissions and contributions to the ambient atmospheric environment have been simulated in China [11–15], India [16], and Japan [17]. On the regional scale, the contributions of thermal power emissions to airborne SO_2 concentration in the Chengdu–Chongqing Economic Zone [18] and airborne $PM_{2.5}$ concentration in the Beijing–Tianjin–Hebei region [19–22] have been simulated. On the city scale, the contributions of thermal power industry emissions to the ambient atmospheric environment (i.e., $PM_{2.5}$ or PM_{10} concentration) have been explored in relation to various cities, e.g., Beijing [23], Jiangsu [24,25], and Shandong [26]. Recently, regional environmental problems have become increasingly prominent, and important areas, such as the "2 + 26" cities, Fen-Wei Plain, and Yangtze River Delta region have become national strategic areas of China's Blue Sky Protection Campaign. However, recent research does not reflect the impact on air quality of the implementation of the latest ULE standards regarding the thermal power industry of the Fen-Wei Plain. Therefore, using the CAM$_X$ air quality model, this study examined the impact on air quality of the ULE standards imposed on the thermal power industry of the Fen-Wei Plain.

To the best of our knowledge, since the implementation of a series of national emission standards for the thermal power industry in China, this study might be the first to examine the contribution of thermal power industry emissions to air quality on the Fen-Wei Plain, using the corresponding emission inventory. The major innovations of this study comprise the following two aspects: (1) Comprehensive Air Quality Model with extensions (CAMx) was a popular source-oriented model, which particularly specializes

in capturing synergistic effects among multiple pollutants involved in different atmospheric physical processes and chemical reactions, and was used in this paper to reflect the real emission characteristics to investigate the impact of thermal power emissions on air quality on the Fen-Wei Plain; (2) the effect of the implementation of ULE standards on the thermal power industry of the Fen-Wei Plain was evaluated.

The main objective of this study was to explore the overall impact on air quality of the emissions of the thermal power industry on the Fen-Wei Plain in 2015 and 2018. The remainder of the paper is organized as follows. The methods proposed for the emission inventory and the air quality simulation are described in Section 2. In Section 3, the contribution results are thoroughly analyzed, and specific policy-related suggestions are offered regarding control of thermal power industry emissions. Section 4 concludes the paper and suggests possible directions for future research.

2. Materials and Methods

This study used the high spatial and temporal resolution Thermal Power Industry Emission Inventory (HPEC) and CAMx model version 6.8 to examine the emissions of the thermal power industry on the Fen-Wei Plain and their contribution to air quality. The study area is described in Section 2.1. Details of HPEC, the emission factors and the model simulation are presented in Sections 2.2., 2.3., and 2.4., respectively, together with descriptions of the corresponding analytical techniques. Section 2.5 explains how the mitigation effects of the ULE standards policy were investigated using a historical scenario of thermal power industry emissions.

2.1. Study Area

The Fen-Wei Plain (33°33′–38°42′ N, 106°20′–114°7′ E), which comprises the Fen-he Plain, Wei-he Plain, and Taiyuan terrace, is the largest impingement plain in the middle reaches of the Yellow River (Figure 1). Including some cities in Shaanxi and Henan, the total area of the Fen-Wei Plain is approximately 10,000 km^2. Through ARCGISv10.6 software, the scale of thermal power enterprises in each city in this region is displayed. (Figure 2). In 2018, 6 of the 20 cities in China with the poorest air quality were located on the Fen-Wei Plain, with a proportion of average good days of 54.3% and an average $PM_{2.5}$ concentration of 58 mg/m^3 (National Ecological and Environmental Quality Overview, 2018).

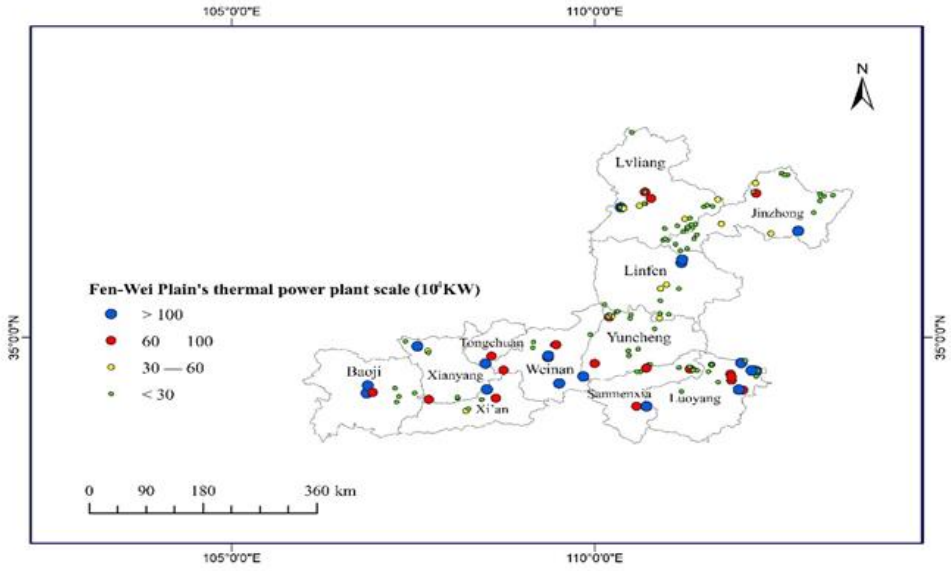


Figure 1. Location and distribution of thermal power generating capacity on the Fen-Wei Plain.

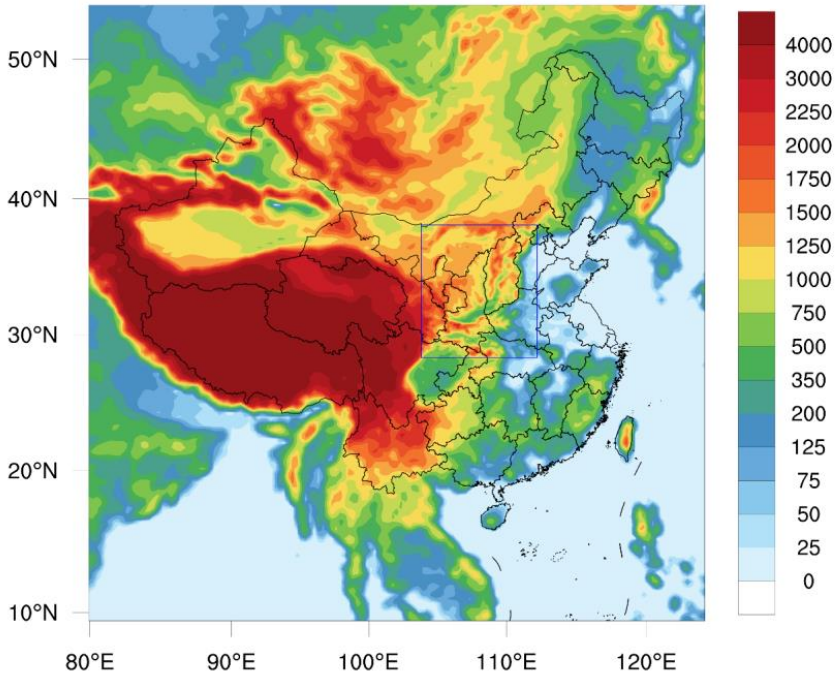
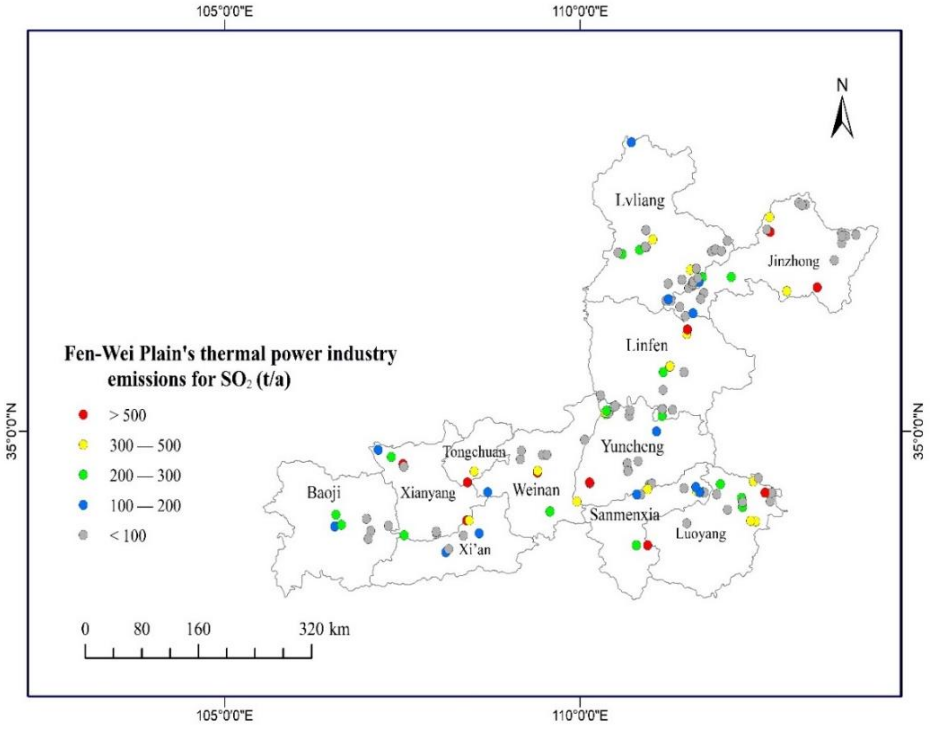
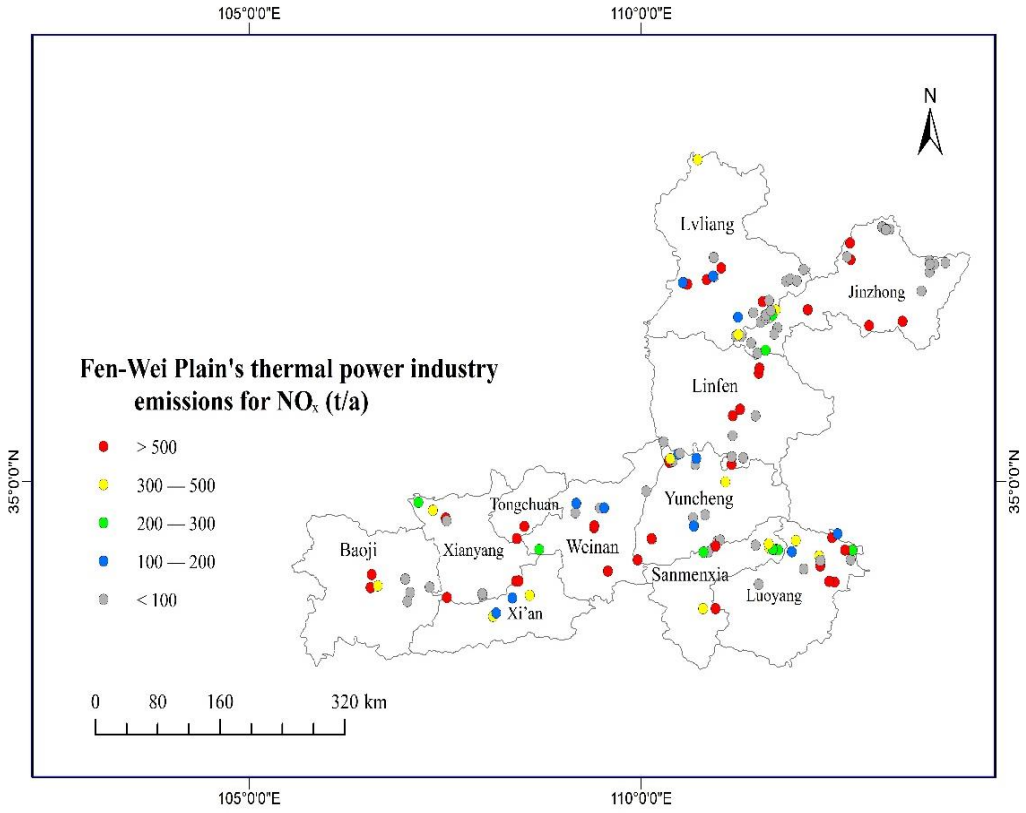


Figure 2. Schematic of the nested grids used for the simulation.

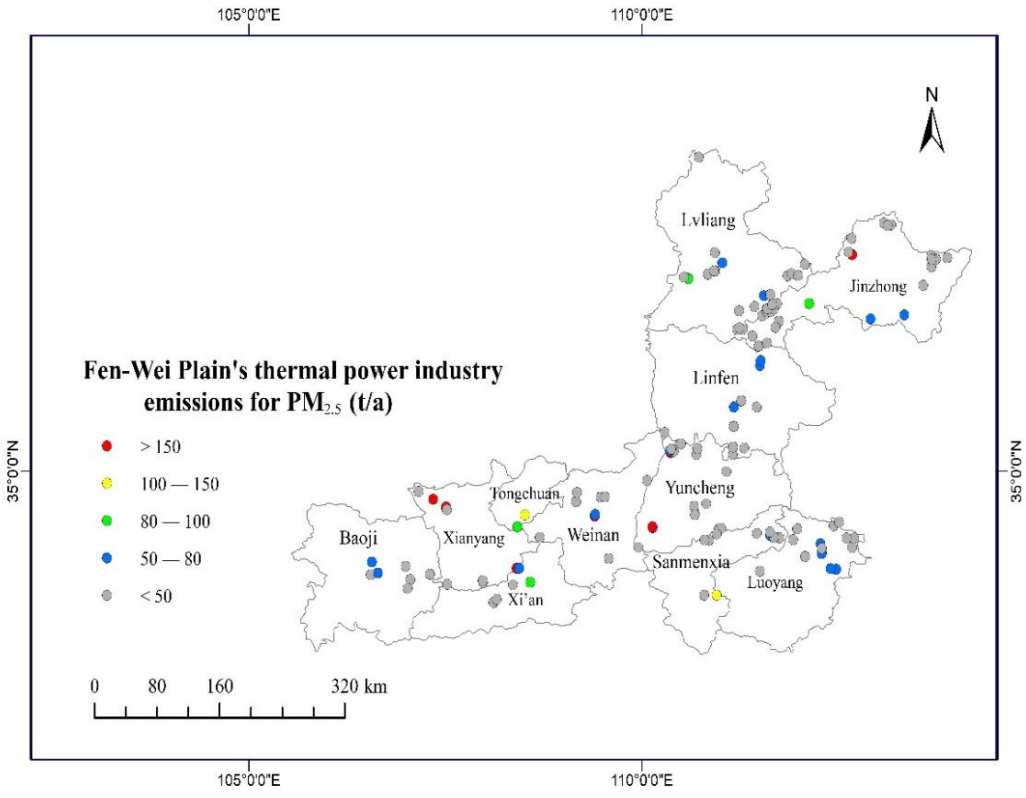
This study incorporated the Xi Xian New Area into Xianyang and the Yangling Demonstration Area into Xi'an, considering administrative divisions and areal coverage. The distribution of thermal power enterprises is shown in Figure 3. It can be seen that the thermal power enterprises in Jinzhong, Lvliang, and Luoyang are reasonably concentrated, distributed mainly in Shanxi and Henan.



(**a**)



(**b**)



(**c**)

Figure 3. Spatial distribution of the thermal power industry emissions (2018) on the Fen-Wei Plain: (**a**) SO_2, (**b**) NOx, and (**c**) $PM_{2.5}$.

2.2. Emission Estimation

This study adopted the HPEC for the Fen-Wei Plain area. HPEC is a list established by our research team [27], which provides detailed information regarding process equipment, environmental protection measures, and production capacity of 143 thermal power enterprises on the Fen-Wei Plain. The geographical location of each power plant was validated using Google Earth®.

The main method to establish the list is Formula (1) [27]. According to the online monitoring annual pollutant concentration data and the theoretical smoke volume of fuel, the emission factors of each thermal power enterprise are obtained as Equation (3). The emissions of each thermal power enterprise are estimated by combining the fuel consumption of environmental statistics enterprises. For an enterprise without CEMS, the emission concentration of the enterprise is represented by the statistical eigenvalues of the same type of unit and the same standard.

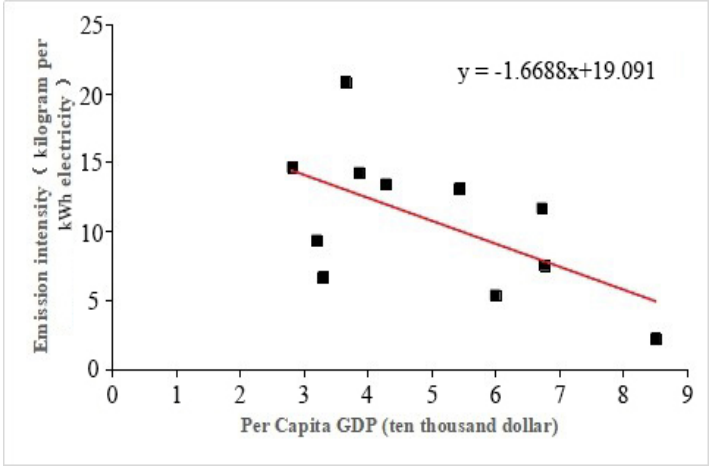
$$Em = \sum_{n}\sum_{i} AC_{n,i} \times EF_{n,i} \quad (1)$$

$$C_{AVG_{n,i}} = \frac{\sum_j \sum_h C_{j,h}}{\sum_j Oph_j} \quad (2)$$

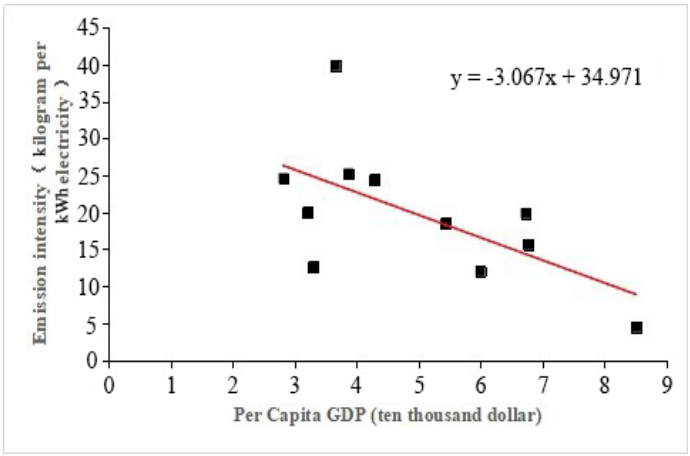
$$EF_{n,i} = C_{AVG_{n,i}} \times V_{n,i} \quad (3)$$

where E_m is the emissions, $t \times a^{-1}$, EF is the emission factor, $g \times \mathrm{kg}^{-1}$, AC is environmental statistical fuel consumption, $t \times a^{-1}$, n distinguishes different cities; i distinguishes between different power plants, C_{AVG} is the statistical mean of emission concentration, $\mathrm{mg} \times m^{-3}$, $C_{j,h}$ is the hourly mean value of pollutant concentration at the online monitoring outlet, $\mathrm{mg} \times m^{-3}$, j is the number of the outlet, h is the number of running hours, Oph is the monitoring hours included in the analysis, and V is the theoretical smoke volume, $\mathrm{mg} \times m^{-3}$ (the smoke volume of other fuels can be estimated by referring to the Manual of the Coefficient of Production and Emission of Industrial Pollution Sources in the First National Pollution Source Census).

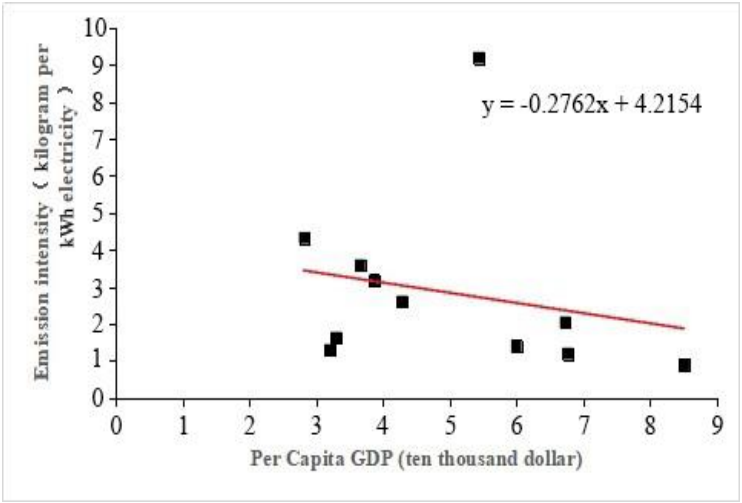
The emissions of SO_2, NO_X, $PM_{2.5}$, PM_{10}, CO, black carbon (BC), and volatile organic compounds (VOC_S) in the production processes of the power plants are estimated based on the unit level. The geographic locations and power generation capacity of the power plants on the Fen-Wei Plain are shown in Figure 4. As can be seen from Figure 5, thermal power units are mainly distributed in Lvliang, Jinzhong, Yuncheng, and Luoyang of Shanxi and Henan Province, with installed capacity accounting for about 49.1%. Large-scale thermal power enterprises are mainly distributed in the south of the Fen-Wei plain, while in the north they are mostly medium- and small-scale enterprises.



(**a**)



(**b**)



(**c**)

Figure 4. Per capita gross domestic product (GDP) of 14 cities on the Fen-Wei Plain plotted against thermal power industry emissions (2018): (**a**) SO_2, (**b**) NO_x, and (**c**) $PM_{2.5}$.

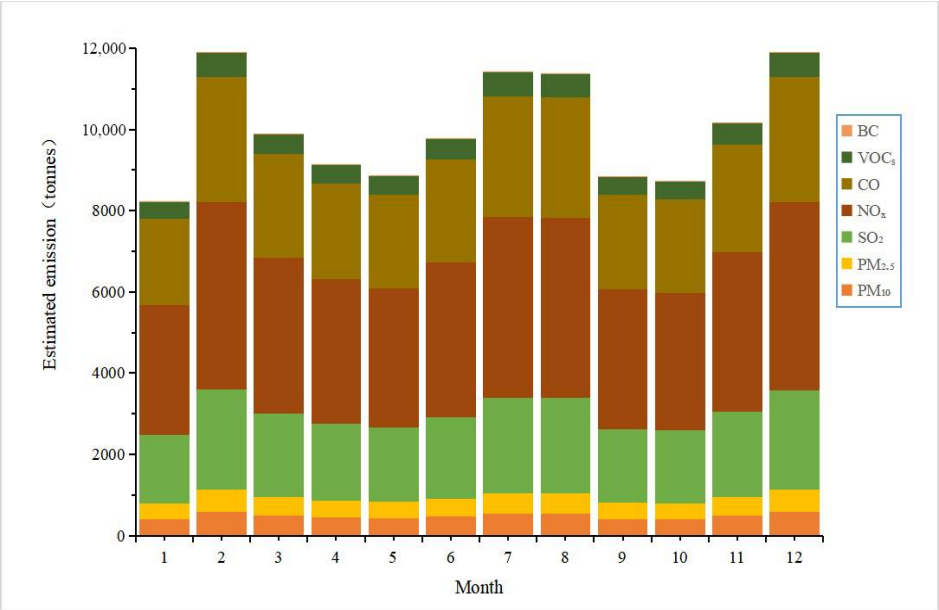


Figure 5. Monthly emission of pollutant species by the thermal power industry on the Fen-Wei Plain in 2018.

Regarding the emission concentrations of SO_2, NOx, and $PM_{2.5}$ at all sites in the study, the emission concentrations in the pollutant emission inventory based on Multi-resolution Emission Inventory for China (MEIC) data are lower than those in the pollutant emission inventory based on high-resolution grid data, with a difference of 10.4–154.5 times. The spatial proportions of pollutant emission concentration stations in the two inventories are basically the same, indicating that the data sources and processing processes of the two inventories have certain reliability and authenticity.

2.3. Emission Factors

The average emission factors of pollutants from different fuel units is shown in Table 1. The emission factor of coal generating units is based on Equation (3). The non-coal generating units are not counted due to the small number of samples, which is quoted from the research results of our team [27].

Table 1. Average emission facts of thermal power using varied fuel.

Species	SO_2		NOx		PM_{10}	
	2018	**2015**	**2018**	**2015**	**2018**	**2015**
Coal/(g × kg^{-1})	0.24	0.69	0.41	0.83	0.06	0.16
Gas/(g × m^{-3})	0.09	0.18	0.44	0.78	0.04	0.06
Fuel/(g × kg^{-1})	1.91	7.5	1.37	2.2	0.67	1.7
Biomass/(g × kg^{-1})	0.23	0.55	0.5	0.87	0.09	0.1

From Table 1, the emission factors of different fuel units are from high to low, which are fuel oil, coal, biomass, and gas, and the emission factors of fuel generator sets are much higher than other fuels. The overall emission factors of non-coal-fired generating units in 2018 are smaller than those in 2015, due to the continuous reduction of the scale of oil-fired generators in China in recent years, while the continuous rise of biomass power generation and gas-fired power generation, the decline in emission factors of non-coal-fired units in the Fen-wei Plain indicates that the control effect of biomass and gas-fired power generation is remarkable.

From the analysis of coal-fired units, the average SO_2 emission factor of coal-fired generating units in Fen-wei Plain in 2018 was 0.24 g × kg^{-1} (down 64% from 2015), the average NOx emission factor was 0.41 g × kg^{-1} (down 50.4% from 2015), and the average pm10 emission factor was 0.06 g × kg^{-1} (down 59.57% from 2015), which was mainly due to the improvement of pollution prevention and control measures.

2.4. Air Quality Modeling

2.4.1. Meteorological Data

In this study, FNL reanalysis data (spatial resolution: 1° × 1°, 6-h intervals) from the US National Center for Environmental Prediction were used as boundary conditions and the background meteorological field, and a new generation mesoscale meteorological Weather Research and Forecasting model (WRF v. 3.9.1) was selected. This model is developed jointly by the US National Center for Environmental Prediction and US National Center for Atmospheric Research, and it has been demonstrated to have reasonable simulation capability in practical application.

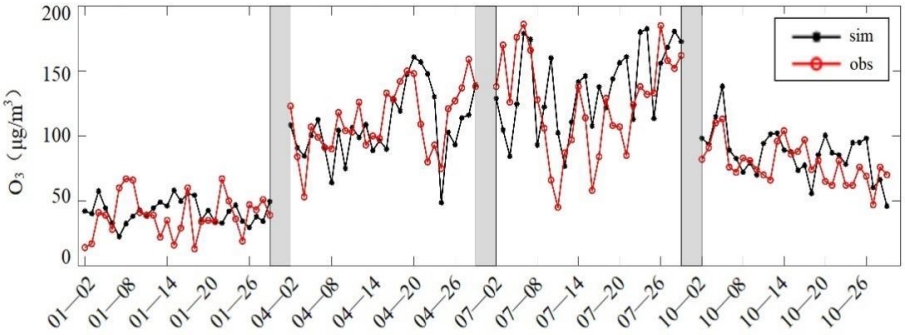
For more accurate modeling, the simulation used two-layered grid nesting: domain D01 covered the entire area of China, and domain D02 covered the area of the Fen-Wei Plain. Domain D01 was used as the background field of the pollutant simulation, while domain D02 focused on simulating the core area of this study. The fully compressible nonstatic equation was adopted, the Arakawa C lattice scheme was adopted in the horizontal direction, and the terrain-following mass coordinate was adopted in the vertical

direction. The selected central point was 35° N, 102° E, and the model was divided vertically into 31 layers with the highest layer at 50 hPa. Lambert Conformal projection is used in this study, which is suitable for China. The true_lat1 was 20° N, and the true_lat2 was 50° N. The main simulation parameters and the nested grid settings are listed in Table 2, and a schematic of the model is illustrated in Figure 6.

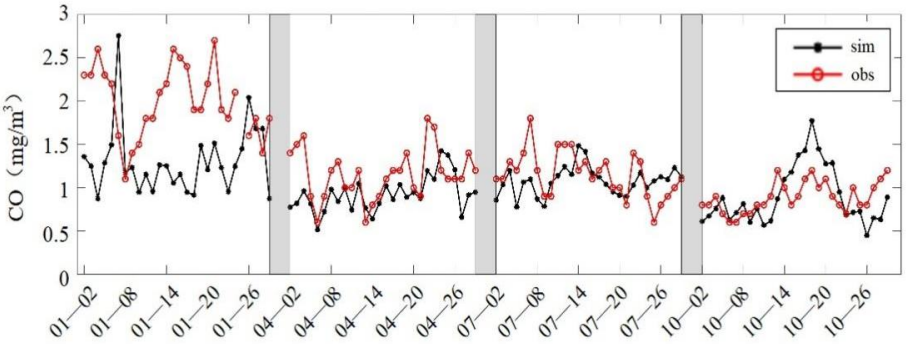
Table 2. WRF model parameter settings.

Pattern	Set Up	Description
WRF	Horizontal grid	144 × 144, 82 × 94
	Grid distance	36 km, 12 km
	Vertical stratification	31
	Cloud microphysics scheme	WSM 5 class scheme
	Surface layer scheme	Monin-Obukhov scheme
	Land surface scheme	Unified Noah land-surface model
	Boundary layer scheme	YSU scheme
	Cumulus parameterization scheme	Kain-Fritsch scheme
	Shortwave radiation scheme	Goddard scheme
	Long wave radiation scheme	RRTM long wave scheme
	Simulation time	January, April, July, and October 2018

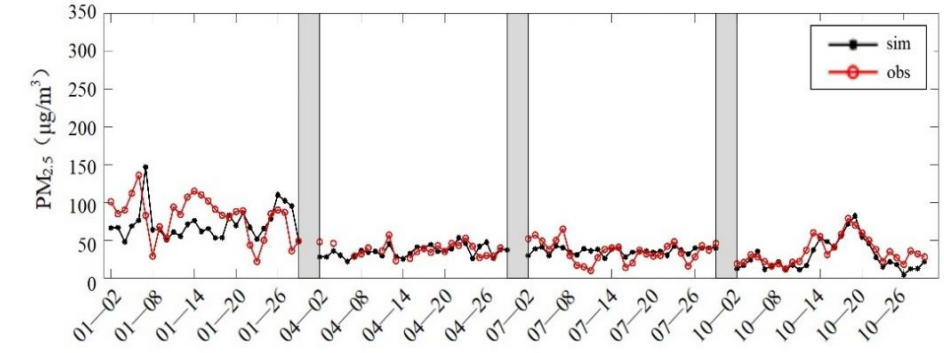
YSU is short for Yousei University, RRTM is short for rapid radiative transfer model.



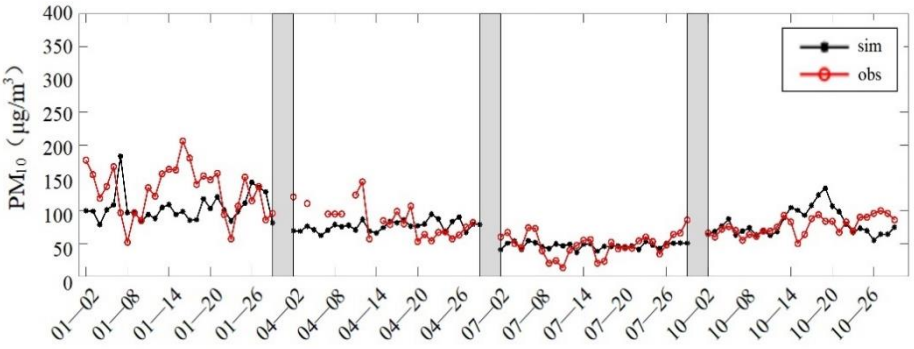
(**a**)



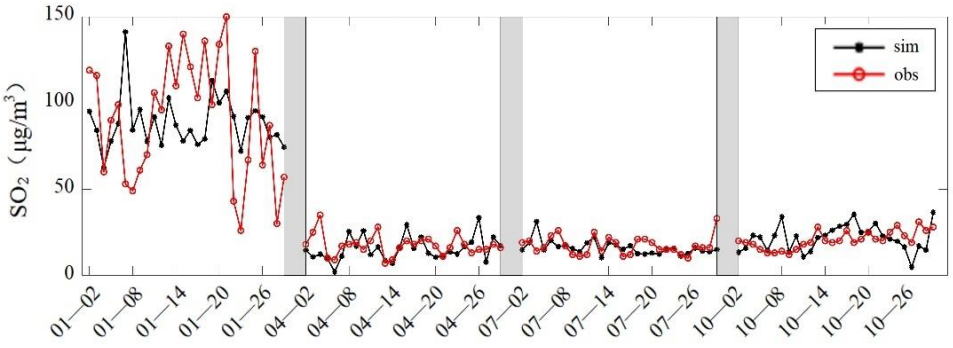
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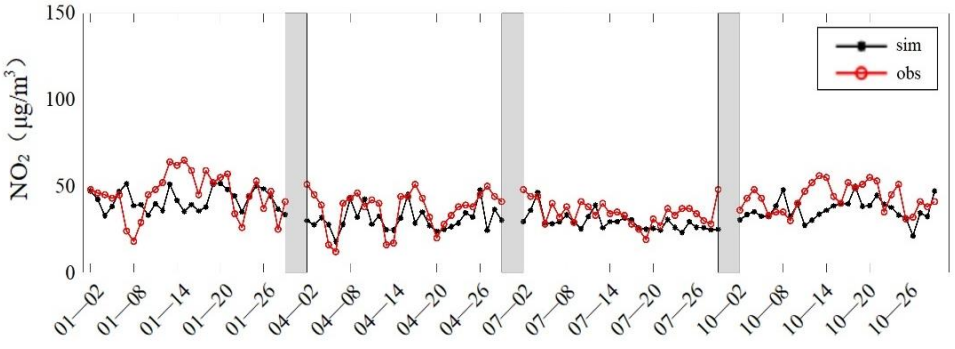
(**c**)



(**d**)



(**e**)



(**f**)

Figure 6. Time series diagram of Lvlian: (**a**) O_3, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) PM_{10}, (**e**) SO_2, (**f**) NO_2.

The WRF topography and surface type data are based on global data of the US Geological Survey, wherein the selected SRTM3 digital elevation data have accuracy of approximately 90 m.

To improve the simulation efficiency, we select typical months to represent different seasons, and then the average of the four seasons is the annual mean. Since January, April, July, and October in northern China respectively represent the typical months of winter, spring, summer, and autumn, and according to the requirements of "Technical guidelines for environmental impact assessment- Atmospheric environment" [28], the meteorological fields in this study are selected as January, April, July, and October, which respectively represent winter, spring, summer, and autumn.

2.4.2. Model Evaluation

The CAMx model, which is a three-dimensional gridded Euler photochemical model, is based on the UAM-V model [29]. It is suitable for simulation of gaseous and particulate air pollutants on urban and regional scales. The CAMx model adopts a two-way nested grid structure that is driven by meteorological fields provided by mesoscale models, such as the WRF, Mesoscale Model5 (MM5), and Regional Atmospheric Modeling System Model (RAMS), and processed using the SMOKE, CONCEPT, and EPS3 models, making it suitable for simulation of the advection, diffusion, deposition, and chemical reaction of atmospheric pollutants. In this study, the mesoscale WRF model was used to provide the meteorological field. CAMx is suitable for urban- and regional-scale air quality simulation of tropospheric O_3, acid deposition, visibility, fine particles, and pollutants. Through this model, environmental management departments can evaluate the impact on the ambient air quality of measures implemented to control multiple pollutants at different scales. The simulation time is consistent with the meteorological field.

The specific parameter settings of CAMx 6.50 adopted for the simulation conducted in this study are shown in Table 3. The selection of this parameter has been applied in many research projects, and good simulation results have been achieved. [4,30]

Table 3. CAMx model parameter settings.

Pattern	Set Up	Description
CAMx V6.50	Horizontal grid	144 × 144, 82 × 94
	Grid distance	36 km, 12 km
	Emission source	MEIC2016 + Thermal power emission source
	Gas phase chemical mechanism	CB05
	Gas phase chemistry algorithm	EBI
	Aerosol mode	AERO5/CF Scheme
	Horizontal advection scheme	PPM
	Vertical diffusion scheme	Standard K theory
	Dry settlement parameterization scheme	WESELY89
	Simulation time	January, April, July, and October 2018

CB05 is a Carbon Bond mechanism, EBI refers to EULER backwards iteration, AERO5 refers to fifth generation aerosol module of CAMx, PPM refers to piecewise parabolic method, WESELY89 refers to Wesely resistance mode.

2.4.3. Verification of Model

According to the "Guidelines for the Selection of Ambient Air Quality Models (Trial)", for the regional Euler grid model, normalized mean bias (NMB), normalized mean error (NME), and Correlation Coefficient (R) are used as the evaluation basis to judge the accuracy of the model. According to the simulated sulfur dioxide (SO_2), nitrogen

dioxide (NO_2), ozone (O_3), fine particulate matter ($PM_{2.5}$), and other pollutants, the corresponding evaluation standards are given, and the evaluation standards for the simulation accuracy of 4 different pollutants as follows:

1. SO_2: −40% < NMB < 50%, NME < 80%, $R^2 > 0.3$;
2. NO_2: −40% < NMB < 50%, NME < 80%, $R^2 > 0.3$;
3. O_3: −15% < NMB < 15%, NME < 35%, $R^2 > 0.4$;
4. $PM_{2.5}$: −50% < NMB < 80%, NME < 150%, $R^2 > 0.3$.

Among them, the R is mainly used to measure the degree of linear correlation between two variables; there is also fractional bias (FB), which is used to quantitatively analyze the consistency between the simulation average of the model and the verification case monitoring average. When the model is underestimated or overestimated twice, FB will exceed the range of −67%~+67%.

2.5. Historical Scenario

To evaluate the mitigation effects attributable to the ULE standards policy, we conducted a historical scenario simulation for 2015 to compare the contribution of thermal power industry emissions to ambient atmospheric concentrations before and after the implementation of the ULE standards policy.

The emission database comprised the HPEC for the Fen-Wei Plain in 2015 [31]. Based on CEMS data in 2015, the annual average discharge concentration of conventional pollutants of each enterprise with online monitoring equipment was calculated. According to the data of low calorific value of coal burning in each enterprise, the theoretical dry smoke volume of each enterprise is calculated. Combined with the theoretical smoke volume and emission concentration information, the emission factors of each enterprise are obtained. Finally, according to the emission factor method, the pollutant discharge of each enterprise is calculated from bottom to top, as shown in Equation 1–3. The CAMx model was used to simulate the contribution of the historical emissions of the thermal power industry to air quality on the Fen-Wei Plain, for which the meteorological data and background emissions were similar to those of 2018.

3. Results and Discussion

Based on the methodology described above, the thermal power industry emissions on the Fen-Wei Plain and their contribution to air quality were explored. In particular, Section 3.1 presents analysis of the thermal power industry emissions on the Fen-Wei Plain with reference to a regional unit-based inventory and compares the emissions in the MEIC list. The comparison between the predicted value and the current monitoring value is in Section 3.2. The corresponding contributions to air quality concentrations, simulated using the CAMx model, are discussed in Section 3.3. Finally, the pollutant emissions from the thermal power industry on the Fen-Wei Plain and their impact on the atmospheric environment in a historical context are analyzed in Section 3.4.

3.1. Thermal Power Industry Emissions on the Fen-Wei Plain

The thermal power industry emissions on the Fen-Wei Plain in 2018 were estimated as follows: 24.8 Gg SO_2, 46.7 Gg NO_x, 5.8 Gg PM_{10}, and 5.5 Gg $PM_{2.5}$. To elaborate more fully, the estimation results are analyzed in terms of spatial, species, and temporal perspectives.

Regarding the spatial distribution, the regional and detailed emissions of the thermal power industry on the Fen-Wei Plain in 2018 are summarized in Figure 7. Two insightful conclusions can be drawn from the results. The first conclusion is that China's thermal power industry emissions have considerable regional variation, with the sources of the highest emissions located mainly in certain areas. For SO_2 emission, Lvliang contributed the largest share (approximately 17.52% of the total in 2018), followed closely by Luoyang (15.13%) and Jinzhong (12.00%). For NO_x emission, Lvliang, Luoyang, and Jinzhong were

the three largest contributors, accounting for 17.82%, 16.70%, and 11.60% of the total, respectively. For PM_{10}, $PM_{2.5}$, and BC emissions, Yuncheng made the largest contribution (14.62%, 14.81%, and 14.81%, respectively), followed by Lvliang (13.43%, 13.68%, and 13.68%, respectively) and Xianyang (12.70%, 12.14%, and 12.14%, respectively). For other pollutants, Jinzhong contributed the largest proportion of emissions (i.e., 20.15% and 18.80% for CO and VOC_S, respectively), followed by Lvliang (15.83% and 16.14%, respectively) and Luoyang (14.51% and 14.97%, respectively). Activity level is the main driving factor of emissions [27], and therefore thermal power industry emissions are generally consistent with the spatial distribution of power generation, with an average Pearson correlation coefficient of 0.52 for all of the aforementioned emission pollutants. This is mainly related to installed capacity and electricity generation. In particular, large enterprises (15.04%) accounted for 49.14% of installed capacity and 50.73% of electricity generation in 2018. It is worth noting that although small enterprises have the largest number of enterprises (64.66%) and emit more pollutants than large enterprises, their installed capacity and electricity generation are the lowest (15.67% and 12.74% respectively), while medium-sized enterprises have a small number (20.30%) but their installed capacity accounts for 35.20%. Power generation accounted for 36.53%. This study found that the number of small enterprises in Lvliang, Luoyang, and Jinzhong accounted for the highest proportion (79.31%, 76.92%, and 50.00%, respectively), which indicates that large-scale and strict control of thermal power enterprises can further promote the emission reduction of air pollutants in China's thermal power industry.

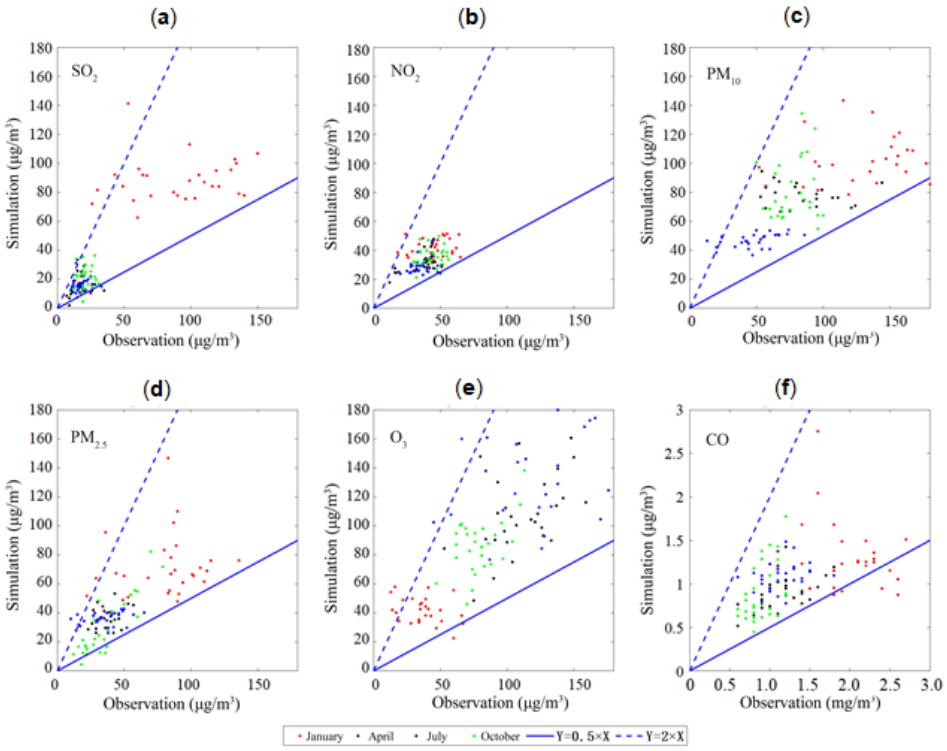


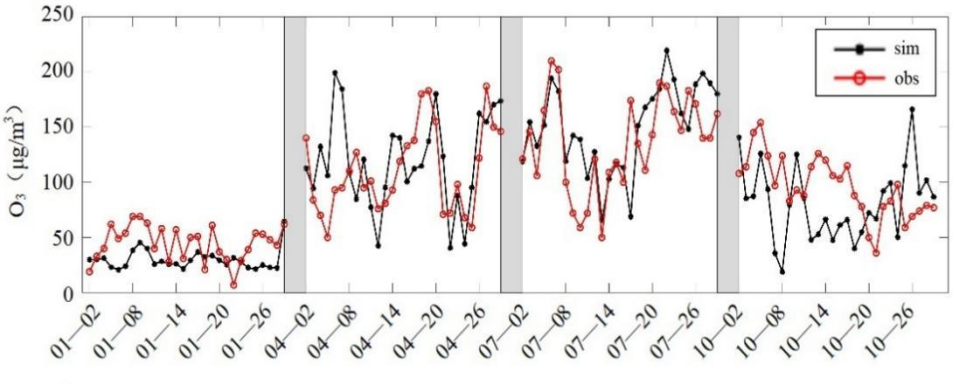
Figure 7. Schema result validation diagram of Lvliang: (**a**) O_3, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) PM_{10}, (**e**) SO_2, (**f**) NO_2.

The second conclusion is that economic level (GDP per capita) has a negative impact on the thermal power industry emission intensity (emission per kW.h of electricity generated) on the Fen-Wei Plain at the municipal level (Figure 4). A linear regression was introduced, and both *t*- and *F*-statistics support this negative contribution statistically at a confidence level of 95% (Table 4). The reason might be that increase in per capita GDP within the region has driven government investment in pollutant treatment technology,

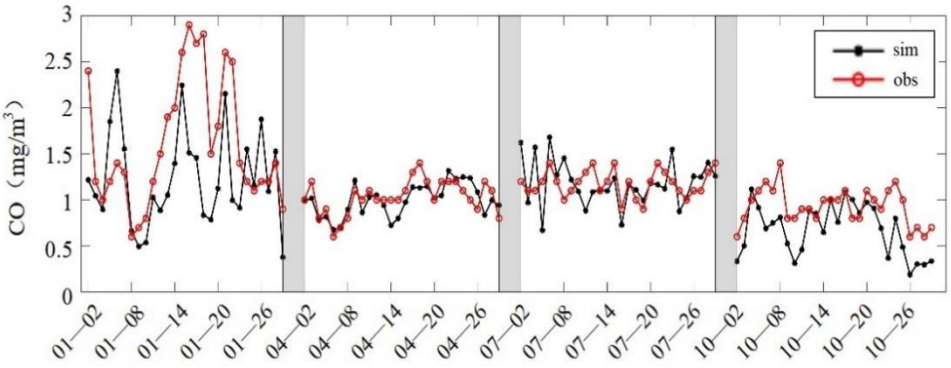
which has led to reduction in energy consumption in the industry. It indicates that economic development is accompanied by continuous upgrading of pollutant treatment technology, i.e., the level of pollution control in economically developed areas is better.

Table 4. Results of linear regression analysis on the relationship between economic level and thermal power industry environmental impact.

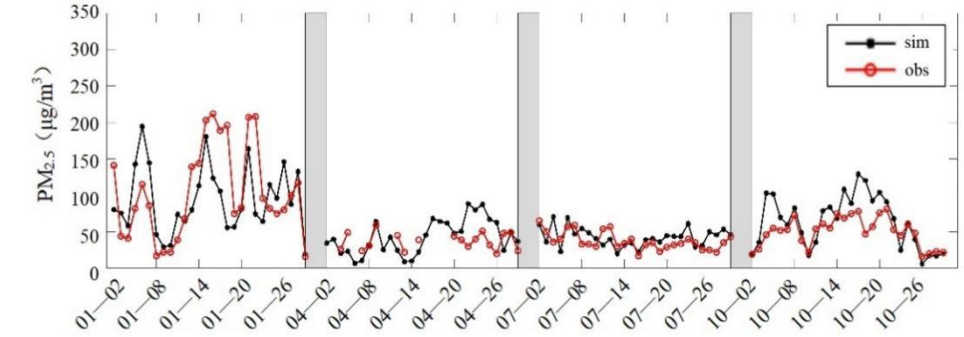
Variable	Model 1 (Y is SO_2; Figure 8a)				Model 2 (Y is NO_x; Figure 9b)				Model 3 (Y is $PM_{2.5}$; Figure 10c)			
	Coefficient	t-Statistic	*p*-Value	Standard Deviation	Coefficient	t-Statistic	*p*-Value	Standard Deviation	Coefficient	t-Statistic	*p*-Value	Standard Deviation
Gross Domestic Product	−0.56	−0.12	0.01	4.75	−0.62	−0.06	0.00	9.72	−0.21	−0.09	0.03	2.29
total sample(N)	11				11				11			
F-Statistic	0.00				0.00				0.44			



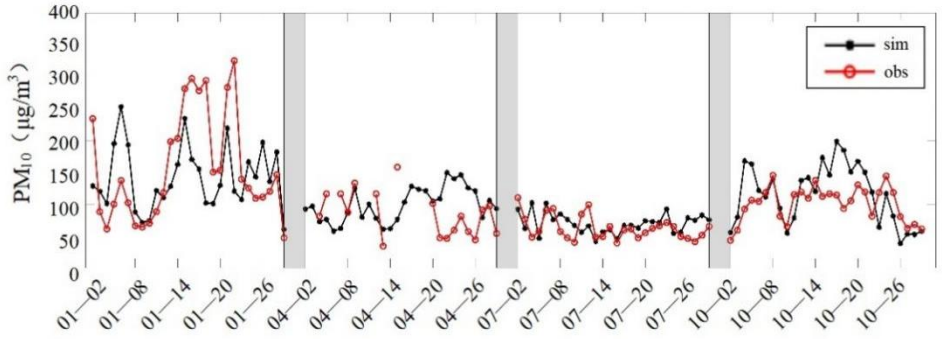
(**a**)



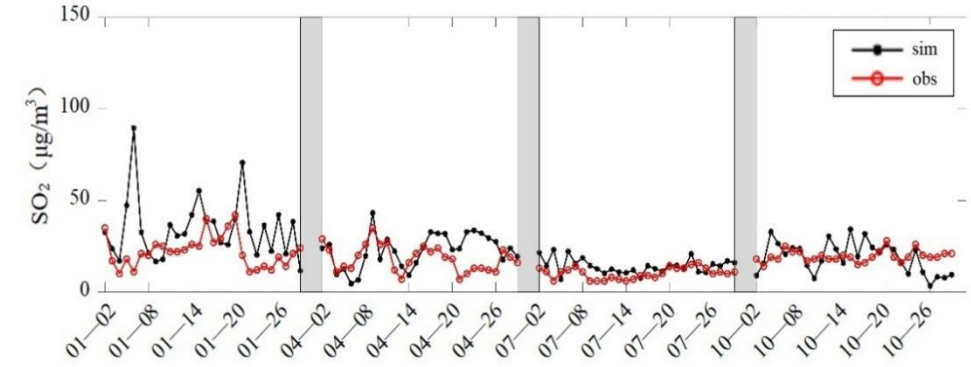
(**b**)



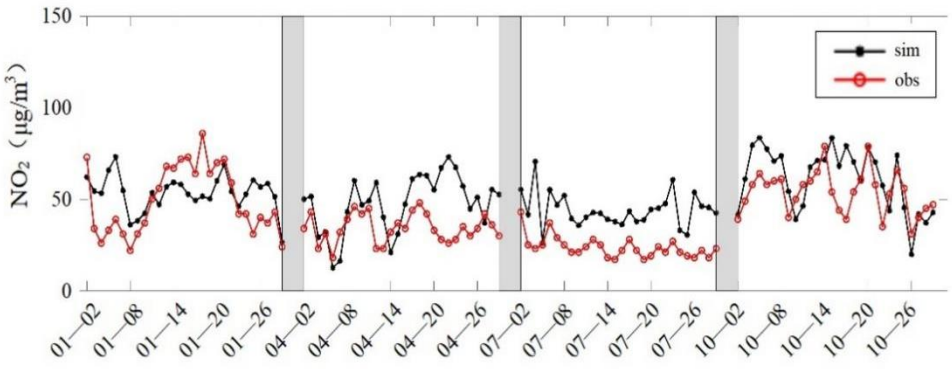
(**c**)



(**d**)



(**e**)



(**f**)

Figure 8. Time series diagram of Luoyang: (**a**) O_3, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) PM_{10}, (**e**) SO_2, (**f**) NO_2.

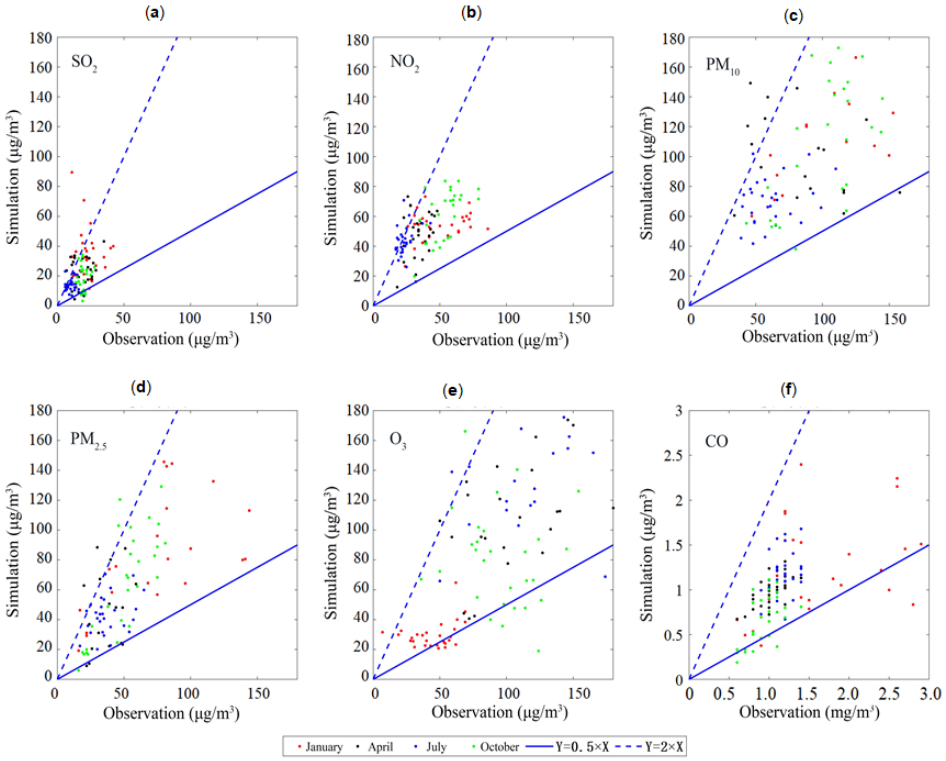
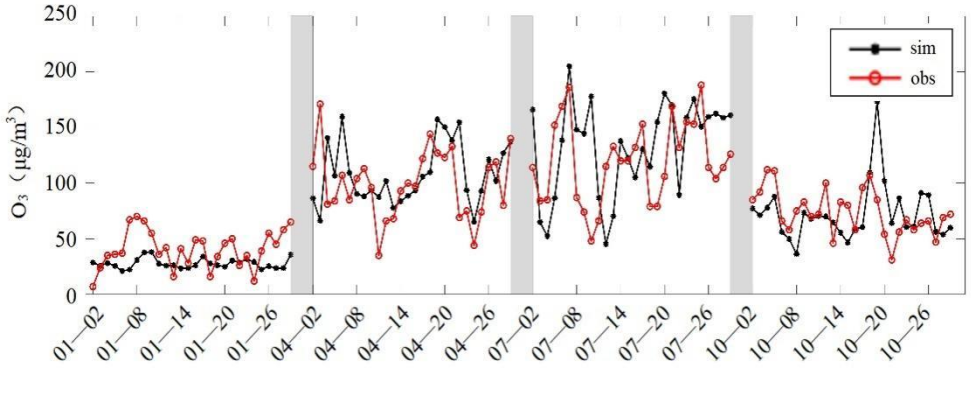
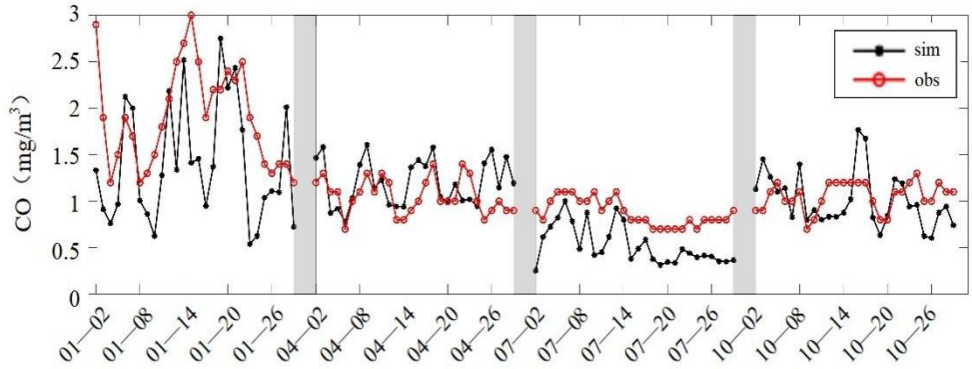


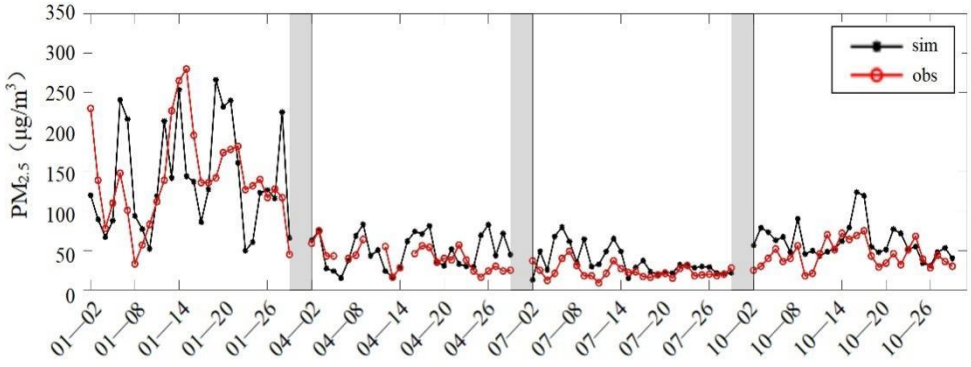
Figure 9. Schema result validation diagram of Luoyang: (**a**) O_3, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) PM_{10}, (**e**) SO_2, (**f**) NO_2.



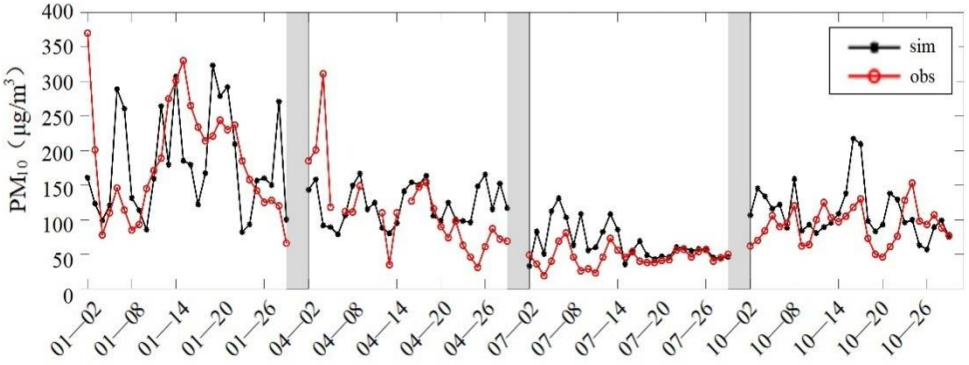
(**a**)



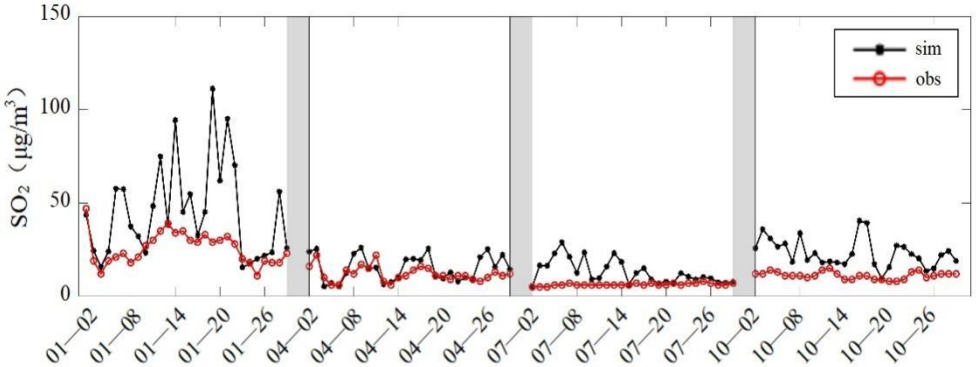
(**b**)


350
300
250
200
150
100
50
0
PM2.5 (μg/m3)
sim
obs
01—02
01—08
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04—02
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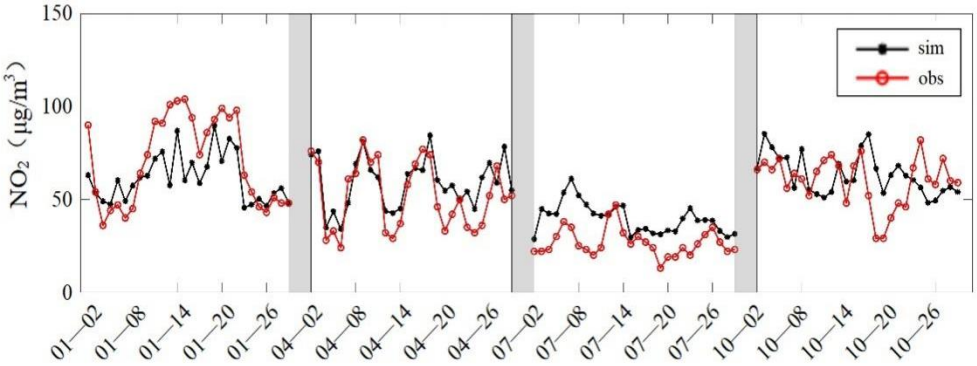
(**c**)


400
350
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150
100
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0
PM10 (μg/m3)
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obs
01—02
01—08
01—14
01—20
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04—08
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04—26
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07—20
07—26
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10—26

(**d**)


150
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SO2 (μg/m3)
sim
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01—02
01—08
01—14
01—20
01—26
04—02
04—08
04—14
04—20
04—26
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07—20
07—26
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10—08
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10—26

(**e**)


150
100
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NO2 (μg/m3)
sim
obs
01—02
01—08
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04—02
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04—20
04—26
07—02
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07—26
10—02
10—08
10—14
10—20
10—26

(**f**)

Figure 10. Time series diagram of Xi'an: (**a**) O_3, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) PM_{10}, (**e**) SO_2, (**f**) NO_2.

From the perspective of species, this study focused on the emission of SO_2, NO_X, and PM (in the form of $PM_{2.5}$). The estimated amounts of NO_X, SO_2, and $PM_{2.5}$ emission by the thermal power industry on the Fen-Wei Plain in 2018 are 46.7, 24.8, and 5.5 Gg, respectively, i.e., the emission of NO_X is 1.88 and 8.49 times greater than that of SO_2 and $PM_{2.5}$, respectively. From the perspective of emission concentration, the online monitoring concentrations of NO_X, SO_2, and $PM_{2.5}$ emission by the thermal power industry on the Fen-Wei Plain are 44.2, 25.6, and 5.5 mg/m^3, respectively, i.e., the emission concentration of NO_X is 1.73 and 8.04 times greater than that of SO_2 and $PM_{2.5}$, respectively. This finding indicates that the emission of pollutant species is directly proportional to emission concentration, and that considerable scope remains for improvement regarding NO_X control.

The temporal trend of monthly emission of pollutant species by the thermal power industry on the Fen-Wei Plain in 2018 is illustrated in Figure 5. Different species generally show similar patterns of monthly emission, indicating that monthly emission profiles are dominated by monthly variations in activity. The largest amount of total pollutant emissions that included 2.45 Gg SO_2, 4.62 Gg NO_X, 0.58 Gg PM_{10}, and 0.55 Gg $PM_{2.5}$ occurred in December, while the minimum amount of total emissions occurred in January. The ratio of monthly total pollutant emissions between the maxima and minima is within the range of 1.44–1.45, which is largely consistent with the monthly variation trend of electricity generation by the thermal power industry nationwide in 2018.

3.2. Model Verification Analysis

Three representative cities with high thermal power distribution and emissions in the Fenwei Plain were selected, the Lvliang site (code 2183A), Luoyang site (1811A), and Xi'an site (1462A), for simulation results verification and analysis. The main selected indicators are shown in Tables 5–7, and the results are shown in Figures 6–11.

Table 5. 2183A station (Lvliang) evaluation index.

Species	R^2	FB	NMB	NME	Mean_Obs	Mean_Sim
$PM_{2.5}$	0.72	−10%	−8%	30%	47.81	43.11
PM_{10}	0.60	−10%	−9%	28%	85.19	77.45
SO_2	0.85	−3%	−3%	34%	36.59	35.40
NO_2	0.47	−15%	−14%	23%	40.04	34.55
O_3	0.78	5%	5%	24%	88.59	93.31
CO	0.42	−21%	−19%	31%	1.29	1.05

R is the correlation between simulated value and observed value, FB is short for fractional bias, NMB is short for normalized mean bias, NME is short for normalized mean error, mean_obs is short for mean observation, mean_sim is short for mean simulation.

Table 6. 1811A station (Luoyang) evaluation index.

Species	R^2	FB	NMB	NME	Mean_Obs	Mean_Sim
$PM_{2.5}$	0.66	3%	7%	41%	58.97	60.91
PM_{10}	0.53	4%	5%	38%	102.54	106.21
SO_2	0.33	25%	28%	52%	17.57	22.56
NO_2	0.53	25%	28%	40%	40.26	51.56
O_3	0.73	−2%	−2%	32%	96.73	94.86
CO	0.53	−15%	−14%	25%	1.19	1.02

R is the correlation between simulated value and observed value FB is short for fractional bias, NMB is short for normalized mean bias, NME is short for normalized mean error, mean_obs is short for mean observation, mean_sim is short for mean simulation.

Table 7. 1462A station (Xi'an) evaluation index.

Species	R^2	FB	NMB	NME	Mean_Obs	Mean_Sim
$PM_{2.5}$	0.77	12%	15%	43%	63.24	71.57
PM_{10}	0.62	10%	11%	40%	108.63	120.01
SO_2	0.73	55%	75%	80%	13.77	24.16
NO_2	0.75	6%	7%	25%	52.31	55.75
O_3	0.69	2%	2%	33%	83.37	85.27
CO	0.62	−17%	−15%	30%	1.23	1.04

R is the correlation between simulated value and observed value, FB is short for fractional bias, NMB is short for normalized mean bias, NME is short for normalized mean error, mean_obs is short for mean observation, mean_sim is short for mean simulation.

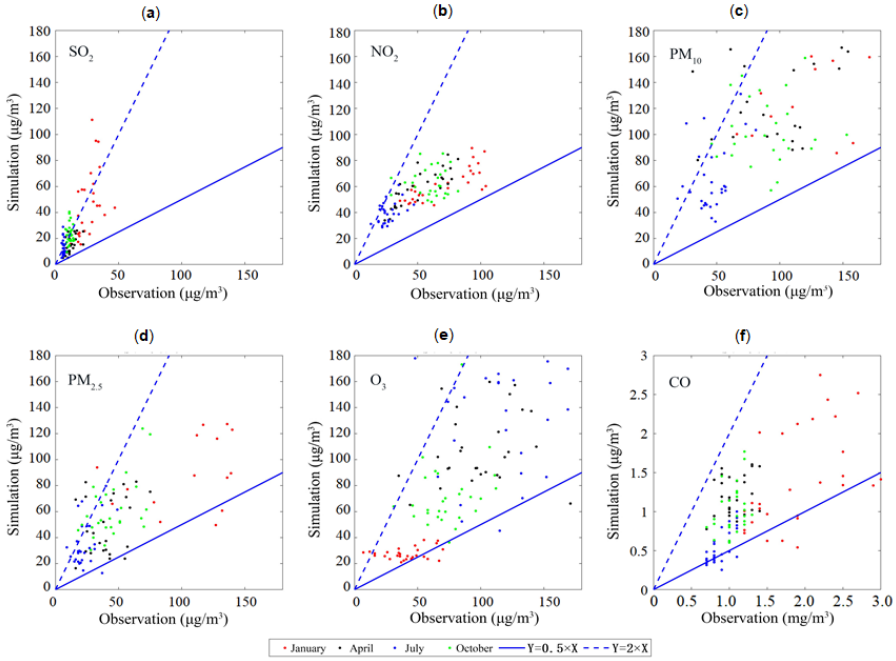


Figure 11. Schema result validation diagram of Xi'an: (**a**) O_3, (**b**) CO, (**c**) $PM_{2.5}$, (**d**) PM_{10}, (**e**) SO_2, (**f**) NO_2.

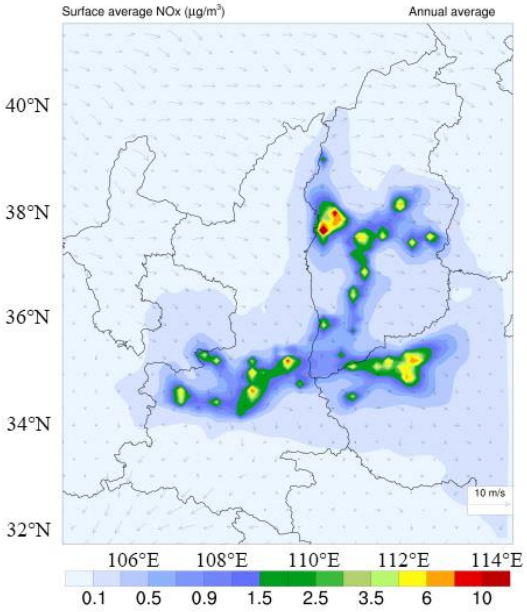
Among them, R^2 between the $PM_{2.5}$ simulation result and the observed value is between 0.66 and 0.77, and the simulation effect is good. It can also be seen from the time series diagram that the model captures the change trend of $PM_{2.5}$ well. The SO_2 simulation effect of the Luoyang site (1811A) is slightly worse, with a correlation coefficient of 0.33. The main reason may be that the inventory used in the simulation is MEIC2016, but the actual emissions of SO_2 and NO_2 in 2018 are lower than the inventory, resulting in an overestimation of the simulation. Circumstances in turn make the O_3 concentration underestimated.

According to the "Guidelines for Selection of Ambient Air Quality Models (Trial)", the simulation accuracy of the 6 conventional factors meets the relevant accuracy requirements.

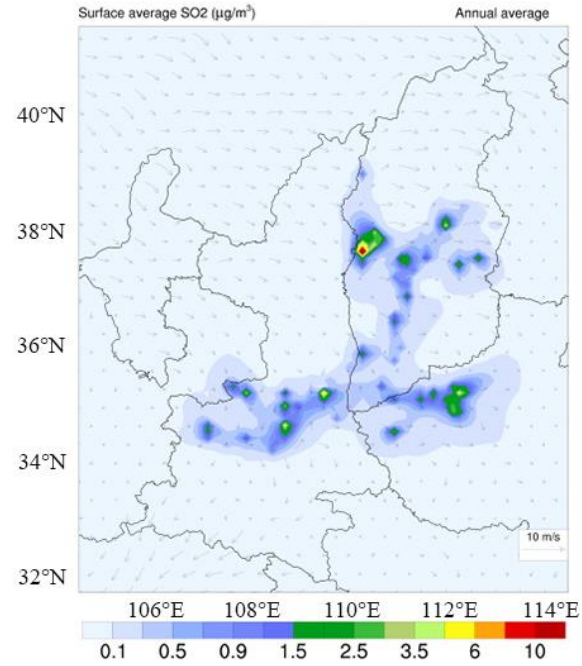
3.3. Air Quality Contribution

The contribution of emissions from the thermal power industry on the Fen-Wei Plain to air quality was investigated using the CAMx model, and the results are analyzed in terms of incremental concentrations and incremental rates (%) from spatial, species, and temporal perspectives.

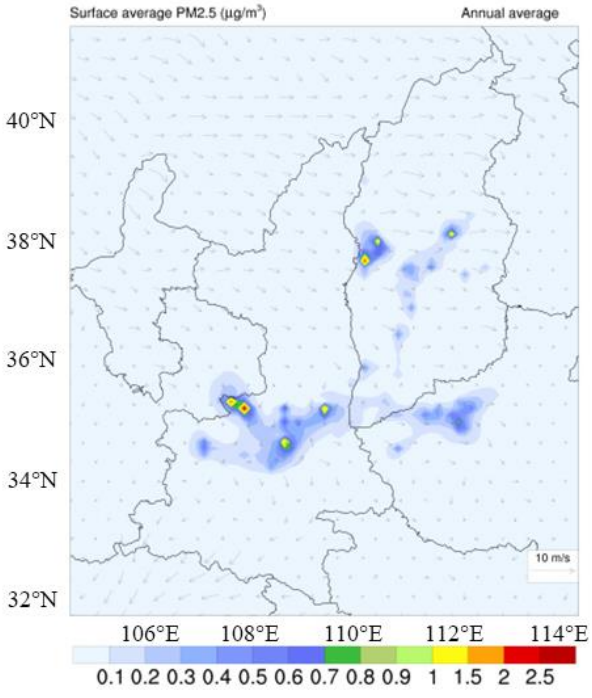
The spatial distribution of the contribution of the thermal power industry on the Fen-Wei Plain to the annual mean concentration of major atmospheric pollutants in 2018 is shown in Figure 12. In terms of the urban contribution, the thermal power industry emissions mainly affected Lvliang, Sanmenxia, and Jinzhong. The largest contributions to regional air pollution of SO_2 emission by the thermal power industry on the Fen-Wei Plain were found in Sanmenxia, Lvliang, and Luoyang (8.90%, 8.10%, and 7.77%, respectively); the largest contributions of NO_x were found in Lvliang, Sanmenxia, and Jinzhong (17.07%, 11.88%, and 7.84%, respectively), and the largest contributions of $PM_{2.5}$ were found in Jinzhong, Lvliang, and Luoyang (1.97%, 1.77%, and 1.15%, respectively). The underlying reason is that the spatial distribution is dominated by the comprehensive impact of power generation and air pollution control measurement coverage. The simulation results derived in this study show that the contributions of Lvliang, Sanmenxia, and Jinzhong are greatest, associated with relatively large power generation (i.e., 208.6 × 10^6, 204.78 × 10^6, and 221.8 × 10^6 kWh, respectively).



(**a**)



(**b**)



(**c**)

Figure 12. Contribution of air pollutants emitted by the thermal power industry on the Fen-Wei Plain in 2018 to ambient concentration in terms of incremental concentrations: (**a**) NO_X, (**b**) SO_2, and (**c**) $PM_{2.5}$.

The air quality impact in important areas, such as the cities of the "Guanzhong Area" is of particular interest following the implementation of China's Blue Sky Protection Campaign. The contribution of the thermal power industry on the Fen-Wei Plain to the ambient environment in such areas in 2018 was investigated. In the "Guanzhong Area" cities, the thermal power industry on the Fen-Wei Plain contributes more to the concentration of major air pollutants in Tongchuan (4.35%, 6.02%, and 0.95% for SO_2, NO_X, and $PM_{2.5}$,

respectively), Xi'an (1.61%, 1.73%, and 0.52%, respectively), and Xianyang (1.36%, 1.53%, and 0.47%, respectively).

In terms of species, this research mainly explored the contributions of SO_2, NO_X, and $PM_{2.5}$. In 2018, the thermal power industry on the Fen-Wei Plain contributed 4.21%, 5.74%, and 0.86% to the annual mean concentration of SO_2, NO_X, and $PM_{2.5}$, respectively. It indicates that NO_X makes a substantial contribution to the regional pollutant concentration, and that considerable scope remains for improvement regarding NO_X control. The results show that the contribution proportion of each component in different cities in the Fenhe and Weihe plain is basically the same, and $PM_{2.5}$ is mainly affected by FPRM + FCRS, POA + SOA, and PNO_3 (Figure 13). It indicates that the particulate matter of thermal power industry is mainly primary pollution in most areas of Fen-Wei Plain, and primary particulate matter is mainly FPRM + FCRS. However, the proportion of nitrate in the secondary particulate matter is larger, which is related to the larger NO_x emissions in the thermal power industry, and is also related to the oxidation of NO_x more easily than SO_2.

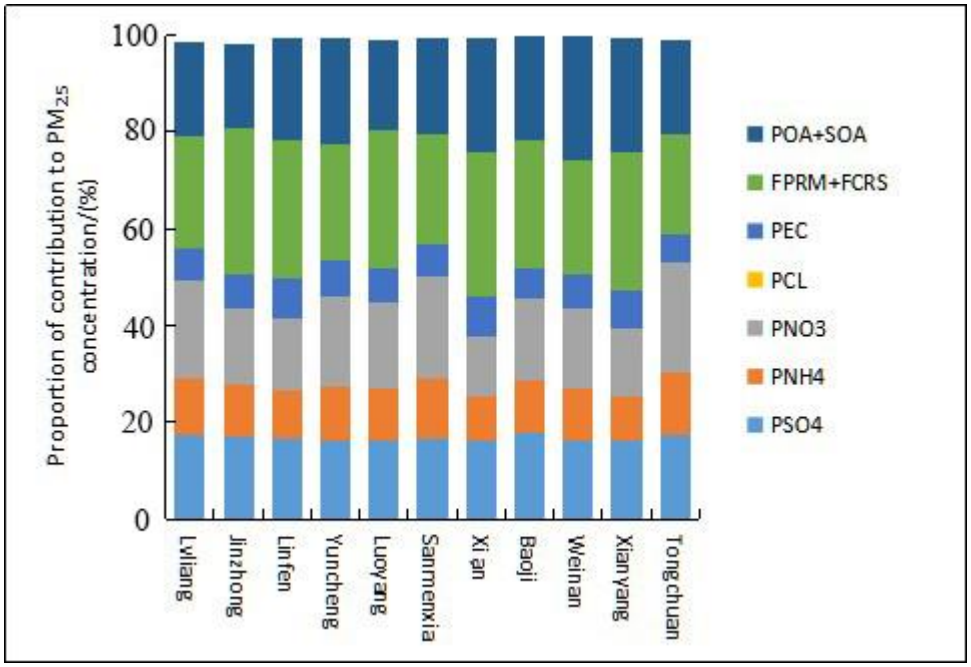


Figure 13. The proportion of each particle in the annual average concentration of total $PM_{2.5}$ in Fen-Wei Plain (%).

From the temporal perspective, the contribution of the thermal power industry on the Fen-Wei Plain to the annual mean concentration of major air pollutants was explored in different seasons (Figure 14).

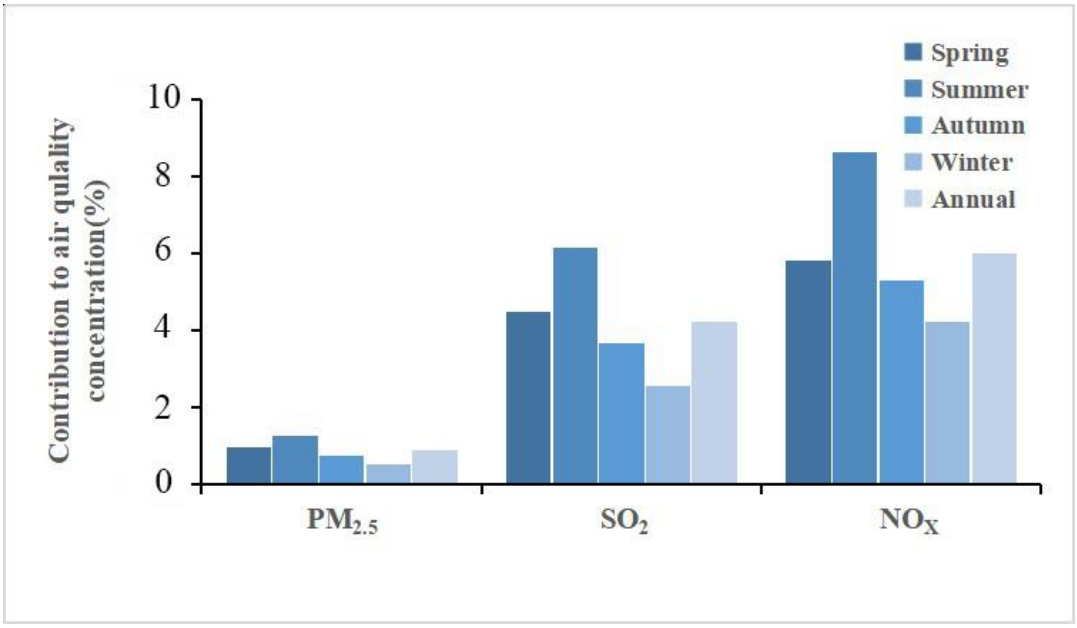


Figure 14. Contribution of air pollutants emitted by the thermal power industry on the Fen-Wei Plain to air quality concentration in 2018.

In this study, January, April, July, and October were selected to represent winter, spring, summer, and autumn, respectively [7]. Simulation results show that the greatest contributions are in summer (i.e., 6.16%, 8.34%, and 1.26% for SO_2, NO_X, and $PM_{2.5}$, respectively) and the smallest contributions are in winter (i.e., 2.54%, 3.93%, and 0.51% for SO_2, NO_X, and $PM_{2.5}$, respectively), similar to the findings of [23]. Although the contribution concentration of pollutants is consistent with the distribution of pollutant emissions, atmospheric diffusion conditions are better in summer, which means air pollution is generally lighter in this season [31]. Figure 15. shows the contribution of sulfate (PSO_4), granular ammonium salt (PNH_4), granular nitrate (PNO_3), granular chloride ion (PCL), primary element carbon (PEC), fine particulate matter and fine crustal particles (FPRM + FCRS), primary organic aerosol and secondary organic aerosol (POA + SOA) to $PM_{2.5}$ concentration. The results show that the contribution proportion of different components is mainly affected by season, and winter has the greatest influence on $PM_{2.5}$.

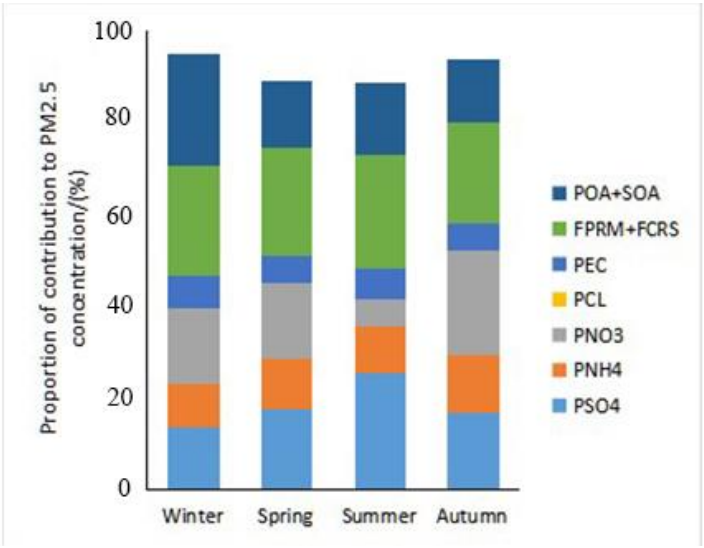
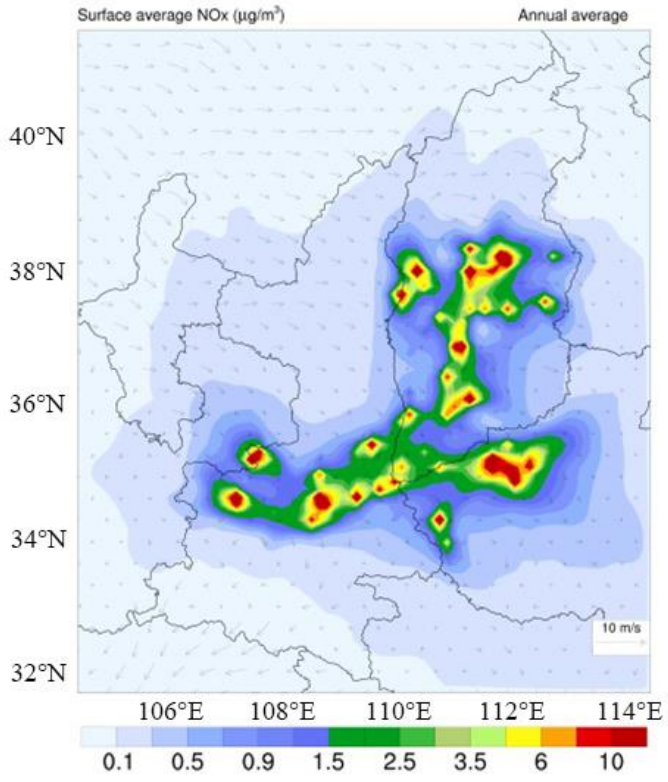


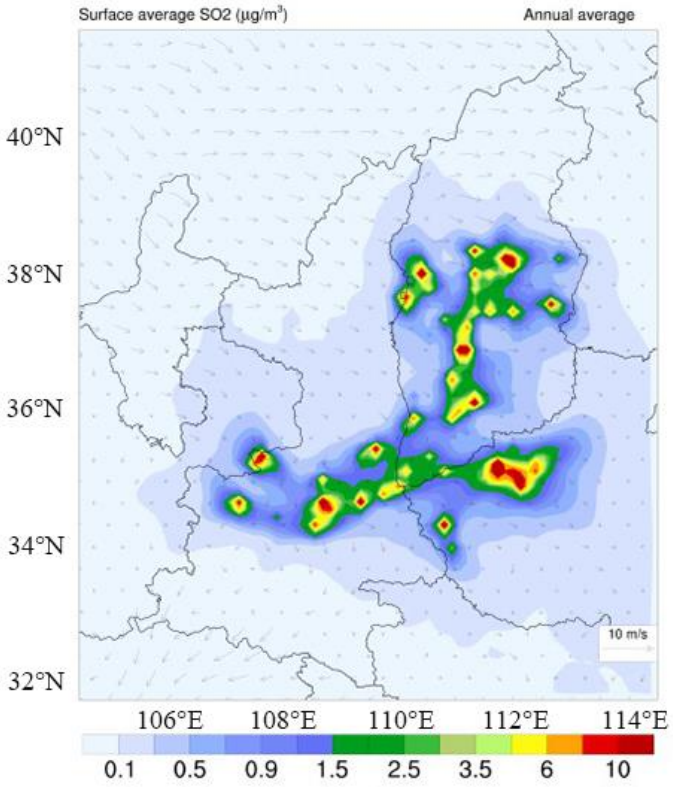
Figure 15. The proportion of particulate matter to the average concentration of $PM_{2.5}$ in each season in Fen-Wei Plain (%).

3.4. Scenario Analysis

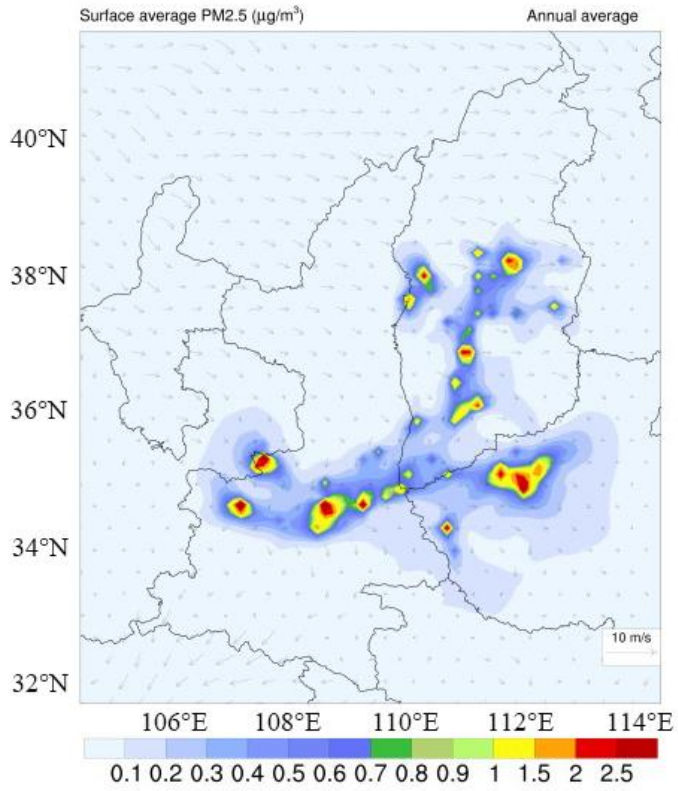
The emissions of the thermal power industry on the Fen-Wei Plain in 2015 were estimated as follows: 58.1 Gg SO_2, 65.2 Gg NO_X, 11.4 Gg PM_{10}, and 9.9 Gg $PM_{2.5}$. For the historical scenario of 2015, the contribution of the thermal power industry on the Fen-Wei Plain to the annual mean concentration of major air pollutants is displayed in Figure 16. In comparison with the historical scenario, the current scenario reveals a striking downtrend in contribution concentrations averaged across the Fen-Wei Plain. The analysis regarding the reduction of emissions focuses on two issues: emissions cuts and ratios.



(**a**)



(**b**)



(**c**)

Figure 16. Contribution of air pollutants emitted by the thermal power industry on the Fen-Wei Plain to ambient concentration in the historical scenario in terms of incremental concentrations: (**a**) NO_X, (**b**) SO_2, and (**c**) $PM_{2.5}$.

From the species perspective, we find that between 2015 and 2018, the annual emissions of SO_2, NO_X, and $PM_{2.5}$ by the thermal power industry on the Fen-Wei Plain decreased by 32.29, 17.48, and 4.34 Gg, respectively, and that the reduction rates were 56.82%, 27.44%, and 44.55%, respectively. Such substantial reduction in contributions is closely related to the stricter limiting values of the current standards, with levels of stringency across all processes, surpassing the previous standards by up to 30%, 50%, and 50% for SO_2, NO_X, and $PM_{2.5}$, respectively (GB13223-2003). However, the NO_X limit for the thermal power industry remains high. Therefore, technological improvements could have great potential regarding the control of NO_X emission by the thermal power industry in the future. It is worth noting that although the absolute cut in NO_X emission is relatively large, the reduction proportion is the smallest of the main pollutants. In other words, the volume of NO_X remains large and has a certain potential to reduce emissions. Therefore, the next step should focus on NO_X emission reduction.

Taking SO_2 as an example, the spatial distribution reveals that Luoyang, Linfen, and Jinzhong were the three areas with the largest cuts in emissions with reductions of 9.89, 5.98, and 5.63 Gg, respectively. Conversely, the emissions in Lvliang increased rather than decreased. Therefore, Lvliang provides targeted opportunities for optimization and adjustment of the structure and layout of the regional thermal power industry to alleviate air pollutant emissions. The areas of Weinan, Xi'an, and Xianyang showed the highest emission reduction ratios (i.e., 83.80%, 83.01%, and 77.49%, respectively) with relatively small reductions. Thus, for these three cities, the scale control and pollutant control of the regional thermal power industry are better.

4. Conclusions

This study marked the first attempt to simulate the contribution of the thermal power industry on the Fen-Wei Plain to air quality at the regional scale. The high-resolution HPEC emissions inventory was introduced to the CAM_X model to systematically explore the contribution of the main pollutant emissions to air quality. The simulation results indicated the following. (1) From the spatial perspective, the air quality contributions were highly concentrated in the Shanxi and Henan areas with high levels of power generation. (2) Among the main pollutants, NO_X made the largest contribution to air quality. (3) From the temporal perspective, the largest (smallest) contribution to air quality concentrations occurred in summer (winter). (4) In terms of policy evaluation, the results verified the efficacy of the current standards implemented in 2014, which have resulted in a substantial reduction in the contribution to air quality by 12.99–47.79%.

Many related topics require further investigation in future research. First, investigation of the public health impact of the thermal power industry would be an insightful extension. Second, it is important to explore the effects of local GDP, the proportion of tertiary industry, meteorological diffusion conditions, and other factors regarding the contribution of the thermal power industry to ambient air quality. We will continue to research the impact of air pollutants associated with the thermal power industry on the Fen-Wei Plain.

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