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Investigating the Influence of the Implementation of an Energy Development Plan on Air Quality Using WRF-CAMx Modeling Tools: A Case Study of Shandong Province in China

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Abstract: In this paper, the Weather Research Forecast (WRF) Comprehensive Air Quality Model with Extensions (CAMx) modeling system with the particulate source apportionment technology (PSAT) module was used to study and analyze the spatial and temporal distribution of atmospheric pollutant concentrations and the source apportionment of fine particles ($PM_{2.5}$) under the base year and an emission reduction scenario in the Shandong province, China. Our results show that industry is the largest contributor of $PM_{2.5}$. In addition, the contribution of key energy-related industries was as high as 29.5%, with the thermal power industry being the largest individual contributor. In January, the largest contribution came from residents, reaching 41.3%. Moreover, loose coal burning in rural areas contributed up to 19.4% in winter. Our results also show that the emission reduction scenario had palpable effects on the reduction of air pollution. The more the emissions of SO_2, NOx, $PM_{2.5}$, and PM_{10} were reduced, the more the average concentration was decreased. The implementation of energy conservation and emission reduction policies by industry and resident is conducive to improving the quality of the atmospheric environment. In particular, a comprehensive control of loose coal burning in winter could significantly improve heavy pollution by particulate matter in winter.

Keywords: energy planning; energy conservation; emission reduction; scenario analysis

1. Introduction

Rapid economic development is often accompanied by large energy consumption and by the generation of atmospheric pollutants, thereby resulting in serious atmospheric environmental problems. The current serious air pollution in China has attracted the attention of the government, the public, and academia [1–3]. Shandong is the major economic province in China, having high energy consumption. The total energy consumption of Shandong ranks first among all the provinces in the country. Due to the unsustainable structure of the energy consumption and the industry of fossil fuels, especially for heating in winter, Shandong is affected by severe air pollution. With continuing industrialization and urbanization, the energy demand will continue to grow at a sustained pace. The contradiction between energy demand and environmental protection faced by Shandong Province is becoming increasingly prominent.

Energy consumption is closely related to the generation of atmospheric pollution. Most of the emissions of sulfur dioxide, nitrogen oxides, and particulate matter produced by anthropogenic activities originate from the burning of fossil fuels and biomass [4]. To date, many studies have been carried out on the relationship between energy consumption and the emission of atmospheric pollutants, both in China and abroad. Econometric models such as long-range energy alternatives planning (LEAP), Stochastic impacts by regression on population, affluence, and technology model (STIRPAT), market allocation (MARKAL), and the factorization model have been used in such studies. These models are often combined with scenario analyses to forecast and plan future energy needs, estimate the corresponding environmental impacts, and perform cost–benefit analyses. In these models, the emissions of atmospheric pollutants and greenhouse gases during energy production, transport, and consumption were calculated, and the scenarios for reducing energy consumption and the impact factors were discussed [5–16].

Analysis of the impacts on the atmospheric environment using these energy–environmental modeling tools mostly focuses on greenhouse gas emissions. There have been relatively few predictive studies on the emissions and effects of common atmospheric pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter, on the atmospheric environment in different energy planning scenarios [17–20]. The regional numerical air quality model can accurately simulate the temporal and spatial variations of atmospheric pollutant concentrations, as well as the contributions of different pollution sources to pollutant concentrations. This model has become one of the mainstream research methods for environmental air quality prediction and pollution source analysis in regional numerical simulations [21]. At present, third-generation air quality models, such as community multi-scale air quality (CMAQ), CAMx, etc., are being widely utilized [22–29]. Many published studies in China used the WRF–CMAQ and WRF–CAMx models to predict the reduction of emissions resulting from the implementation of air pollution control plans or measures in China, the Yangtze River Delta, and the Pearl River Delta [30–39]. Wu et al. and Huang et al. used the CAMx–PSAT model to simulate the characteristics of the particulate matter pollution and its transport in the Pearl River Delta region. They found that the trans-regional transport and mobile sources were the main sources of particulate matter and that their contributions to particulate matter concentrations in winter were 62% and 21%, respectively [40,41]. Allard et al. used the WRF–CAMx–PSAT model to assess the impact of the implementation of Thailand's power development plan on the country's ambient air quality from 2016 to 2036 [42]. Shahbazi et al. found that that the concentration of NOx had decreased by 1.7% after implementing a traffic regulation measure in Tehran, the capital of Iran, using the WRF–CAMx model [43]. All the above studies have shown that using an air quality model is of great significance for the prediction and evaluation of atmospheric environmental impacts and for assessing the effects of the implementation of various energy conservation and emission reduction policies and measures. It would certainly be beneficial to achieve a deeper understanding of the relationships between energy consumption, economic development, energy conservation, and emission reduction, and regional atmospheric environmental quality. This would also be useful for assessing the effectiveness of plan and policy implementation, as well as for identifying and screening targeted strategies and measures to improve the regional atmospheric environment.

At present, the majority of studies on the analysis and prediction of atmospheric environmental quality using air quality models have focused on the impacts of the implementation of traffic regulations, industrial planning, and atmospheric environmental control measures on air quality [44–49]. However, few studies are available on the prediction and analysis of atmospheric environmental impacts after the implementation of energy planning, which is closely related to air pollution [50,51]. This study was based on the "Medium- and Long-Term Energy Development Plan of Shandong Province (2016) (MLED_SD)" and focused on thermal power, steel, chemical, coal, and oil extraction, and other key energy-related industries. The impact of different energy conservation and emission reduction policies and measures on the atmospheric environment in Shandong were analyzed herein.

The study is summarized as follows: using 2015 as the base year, a provincial-level atmospheric pollutant emission inventory (baseline inventory) was developed using a bottom-up approach; by combining the "Medium- and Long-Term Energy Development Plan of Shandong Province" and various government-developed energy conservation and emission reduction policies and measures, an emission scenario for 2020 was prepared; the WRF–CAMx–PSAT air quality model system was used to simulate the temporal and spatial distributions and variations of conventional atmospheric pollutant concentrations in Shandong Province in 2015 and 2020; the contributions of key energy-related industries to the concentrations of fine particulate matter were analyzed. This study is expected to provide important data support for the prediction and assessment of the atmospheric environmental impact of medium- and long-term energy development in Shandong Province, as well as a reference for policy makers at the provincial level to formulate energy conservation and emission reduction policies and measures. This will also provide a reference for future atmospheric environment impact assessments at the provincial level in China that focus on energy-related planning.

2. Methodology

2.1. Study Area

Shandong Province is located on the eastern coast of China. In 2015, the energy consumption of the province accounted for 10% of China's total energy consumption, the highest among all the provinces in China. The consumption of coal also was high, with industrial coal consumption accounting for 96% of the total coal consumption. In particular, coal consumption for power generation accounted for 35% of the total coal consumption [52]. Numerous studies have shown that fossil fuel burning is closely related to primary particulate matter emissions and secondary aerosol generation [30,53–55]. The high energy consumption industry-intensive structure resulted in the heavy dependence of Shandong Province industry on energy. The energy consumption structure dominated by fossil energy, especially coal, has put enormous pressure on the environment, especially the atmospheric environment [56]. Recent monitoring data of ambient air quality in Shandong Province show that particulate matter (especially fine particulate matter) poses the most serious pollution issue [57].

The above analysis demonstrates that due to the energy system with coal as the main component and the industrial structure dominated by high energy consumption and high pollution industry, the environmental problems in Shandong (especially the air pollution problem) have become increasingly serious in recent years.

2.2. Emission Inventory

In this study, a "bottom-up" approach was used to develop a 2015 (base year) Shandong Province atmospheric pollutant emission inventory (baseline emission inventory) on the basis of the Shandong Province Environment Statistics Database and Pollution Discharge Declaration Database. The types of primary pollutants that were considered include sulfur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOCs), ammonia (NH_3), respirable particulate matter (PM_{10}), and fine particulate matter ($PM_{2.5}$). The data required for the calculation of atmospheric pollutant emissions from various sources came from the Shandong Province Environment Statistics Database, the Pollution Discharge Declaration Database, the Shandong Statistical Yearbook, statistical yearbooks of prefecture-level cities in the Shandong Province, and questionnaire data on loose coal burning by the rural residents.

2.2.2. Calculation Method and Emission Factors

The emission coefficient method is the most commonly used method for calculating the emission of various pollutants both in China and abroad [58–60]. The basic principle is as follows:

$$\mathrm{EM}(i, j, k, l) = \mathrm{AC}(i, j, k) \times \mathrm{EF}(j, k, l)$$

where EM is the pollutant emission, AC is the pollutant activity, EF is the emission factor, i is the geographical range of the study area, j is the pollutant emission process, k is the time, and l is the pollutant type.

Table 1 provides the basis for calculating the main atmospheric pollutants from different pollution sources and the emission factors. It should be noted that the SO_2 and NOx emission values from industrial and urban living sources were directly taken from the Shandong Province Environment Statistics Database. The pollutant emissions from on-road mobile and agriculture derive from the multi-resolution emission inventory for China (MEIC) [61]. No special calculation was performed in this paper.

Table 1. The calculation method of the main atmospheric pollutants emission from different pollution sources and the source of the emission coefficient used in this study.

Category	Sub-category	Pollutant	References
Industry	key energy-related industries and other industries	CO	Wang et al., 2005 [58]; Zhao et al., 2008 [59]; Huang et al., 2011 [60]
		$PM_{2.5}$	Technical Guidelines for Preparation of Primary Source Emission Inventory of Atmospheric Fine Particulates (Ministry of Environmental Protection of the People's Republic of China, 2014)
		PM_{10}	Technical Guidelines for the Preparation of Primary Source Emission Inventory of Inhalable Particulates in the Atmosphere (Ministry of Environmental Protection of the People's Republic of China, 2014)
		VOCs	Technical Guidelines for the Preparation of Atmospheric Volatile Organic Compound Emission Inventory (Ministry of Environmental Protection of the People's Republic of China, 2014)
		NH_3	Technical Guidelines for the Preparation of Atmospheric Ammonia Source Emission Inventory (Ministry of Environmental Protection of the People's Republic of China, 2014)
Transportation	road dust	$PM_{2.5}$	Technical Guidelines for the Preparation of Air Pollutant Emission Inventory for Road Vehicles (Ministry of Environmental Protection of the People's Republic of China, 2014)

		PM_{10}	Technical Guidelines for the Preparation of Air Pollutant Emission Inventory for Road Vehicles (Ministry of Environmental Protection of the People's Republic of China, 2014)
	port terminal VOCs emission	VOCs	Technical Guidelines for the Preparation of Atmospheric Volatile Organic Compound Emission Inventory (Ministry of Environmental Protection of the People's Republic of China, 2014)
Resident	urban residents	CO	Wang et al., 2005 [59]; Zhao et al., 2008 [60]; Huang et al., 2011 [61]
		$PM_{2.5}$	Technical Guidelines for Preparing Primary Source Emission Inventory of Atmospheric Fine Particulates (Ministry of Environmental Protection of the People's Republic of China, 2014)
		PM_{10}	Technical Guidelines for the Preparation of Primary Source Emission Inventory of Inhalable Particulates in the Atmosphere (Ministry of Environmental Protection of the People's Republic of China, 2014)
		VOCs	Technical Guidelines for the Preparation of Atmospheric Volatile Organic Compound Emission Inventory(Ministry of Environmental Protection of the People's Republic of China, 2014)
		NH_3	Technical Guidelines for the Preparation of Atmospheric Ammonia Source Emission Inventory (Ministry of Environmental Protection of the People's Republic of China, 2014)
	rural (suburban) residents	SO_2 NOx CO $PM_{2.5}$ PM_{10} VOCs NH_3	Technical Guidelines for the Preparation of Air Pollutant Emission Inventory for Biomass Combustion Sources (Ministry of Environmental Protection of the People's Republic of China, 2014), Technical Guidelines for the Preparation of Civil Coal Air Pollutant Emission Inventory (Ministry of Environmental Protection of the People's Republic of China) , 2016)

2.2.1. Source Categorization

Based on the emission characteristics of atmospheric pollutants, the emission inventory was divided into 4 emission categories, including industrial sources (industry), residential sources (resident), transportation sources (traffic), and agricultural ammonia emission sources (agriculture).

In this study, the main focus was on industries that are closely related to fossil energy development and utilization, have high fossil energy consumption, and high atmospheric pollutant emissions. Based on MLED_SD and the production characteristics and energy consumption of various industries, 10 types of industries were selected as key energy-related industries, namely coal mining, oil mining, coking, refining, chemical, building materials, graphite carbon, steel, non-ferrous metal smelting, and thermal power production. In 2015, the above-mentioned key energy-related industries accounted for 54% of the total number of enterprises, while in terms of coal consumption, they accounted for more than 90%. In addition, considerable loose coal burning occurs in rural and urban fringe areas, and its impact on the surrounding atmosphere environment cannot be ignored [62]. Therefore, in this study, emissions due to loose coal burning were calculated separately and were categorized as a part of the residents' emissions.

2.3. The 2020 Emission Reduction Scenario

On the basis of the MLED_SD, this study predicted a future emission reduction plan called the 2020 emission reduction scenario. The atmospheric pollutant emission inventories for 2020 were developed on the basis of the baseline emission inventory. The future scenario of atmospheric pollutant emissions and spatial distribution in Shandong was constructed using the “bottom-up” approach, by comprehensively considering the MLED_SD, the government’s energy-related policies and plans, the environmental protection plan, the energy conservation and emission reduction action plan, and the emissions standards.

For the 2020 emission reduction scenario, the changes in the emissions of atmospheric pollutants from industry and residents caused by the implementation of energy-related planning were considered. It was assumed that the emissions and spatial distributions from on-road mobile road dust, agriculture, outer domains, and the boundary were consistent with the baseline emission inventory. Based on the above considerations, a projected emissions inventory was developed for the 2020 emission reduction scenario. In this study, relevant policies and plans, as well as various specific measures for energy conservation and emission reduction for 2020, were issued. The document directory of the relevant policies, plans, and measures is given in Table 2.

Table 2. The relevant policies, plans, and measures carried out in the 2020 emission reduction scenario.

Category	Sub-Category	Policies	Measures	Plans
Industry	Thermal power	Eliminate backward production capacity	Prioritize the elimination of units below 200,000 kW, especially pure condensation units operating for 20 years and extraction condensation heat and power units operating for 25 years.	Medium and Long-Term Development Energy Plan of Shandong Province (Development and Reform Commission of Shandong Province, 2016)
			Elimination of conventional coal-fired thermal power units with a capacity of less than 100,000 kW per unit and conventional coal-fired thermal power units with a capacity of less than 200,000 kW per unit at the end of their design life	Shandong Local Implementation Plan for Refining and Chemical Industry Transformation and Upgrading (Shandong Petrochemical Industry Association, Shandong Petroleum Refining and Chemical Association, 2014)
			Elimination of conventional small fossil-fired power units with a single unit capacity of 50,000 kW or less and of oil-fired boilers and generators mainly for power generation	Shandong Province's Elimination of Backward Capacity Coal Mines List (Shandong Coal Industry Bureau, 2016)
			List of the First Batch of Coal and Electricity Industry Planned to Eliminate Backward Productivity Enterprises in Shandong Province	List of the First Batch of Coal and Electricity Industry Planned to Eliminate Backward Productivity Enterprises in Shandong Province in 2017 (Shandong Coal Industry Bureau, 2017)
		Environmental protection reform	Implementation of ultra-low emission environmental protection renovation for	Implementation Opinions of the Shandong Provincial People's Government on

	of ultra-low emission	HUANENG (Dezhou), GUODIAN (Shiheng), HUADIAN (Shiliquan, Weifang) and other nearly 55 million kilowatt coal-fired power units by 2017	Implementing the Pilot Program for the Structural Adjustment of the Iron and Steel Industry in Shandong Province (Shandong Provincial People's Government, 2012)
		Energy-saving reforms have been carried out for nearly 33 million kilowatt coal-fired power units in GUODIAN (Liaocheng), DATANG (Huangdao), HUADIAN (Zouxian), HUARUN (Heze), etc. The coal consumption of the power supply has reached the advanced level of the same type of units.	Shandong Province's Elimination of Backward Capacity Coal Mines List (Shandong Coal Industry Bureau, 2016)
		In 2017, the province's coal-fired units were fully implemented ultra-low emissions, so that the average coal consumption per kilowatt hour in all existing power plants was less than 310 grams of standard coal, and the average coal consumption per kilowatt hour in new power plants was less than 300 grams of standard coal.	Comprehensive Emission Standards of Regional Air Pollutants in Shandong Province (Shandong Environmental Protection Department, 2013)
steel	Eliminate backward production capacity	By the end of 2017, Qingdao city eliminated the backward production capacity of ironmaking by 3.6 million tons; Laiwu city eliminated the backward production capacity of ironmaking by 3.5 million tons. Elimination of coke ovens (with a capacity of 75,000 tons per year or less) with a carbonization chamber height of less than 4.3 meters (except	Notice on Implementing the Work of Eliminating Overcapacity and Realizing the Development of Overcoming Difficulties in Iron and Steel and Coal Industry (Shandong Economic and Information Commission, Shandong Development and Reform Commission, 2016)

	tamping coke ovens with a capacity of 3.8 meters or more) occurred. In 2017, besides total production capacity of the steelworks belong to Jinan Iron and Steel Group Company will be shutdown, and the province planned to reduce crude steel production capacity by 5.27 million tons and pig iron production capacity by 1.75 million tons. Among them: Weifang city reduced the crude steel production capacity by 2.2 million tons and reduced the pig iron production capacity by 550,000 tons. Laiwu city reduced the crude steel production capacity by 1.24 million tons; Binzhou city reduced crude steel production capacity to 1.83 million tons; Linyi city reduced pig iron production capacity to 1.2 million tons; List of enterprises in Shandong's target plan for eliminating backward production capacity in 2015
Reducing energy consumption level	By 2020, the comprehensive energy consumption per ton of steel will be reduced to less than 570 kg of standard coal, the consumption of fresh water per ton of steel will be less than 2.95 tons, the emission of smoke and dust per ton of steel will be

			less than 0.8 kg, and the emission of SO_2 per ton of steel will be less than 1.2 kg.	
	Chemical	Reducing energy consumption level	By 2020, the average comprehensive energy consumption of crude oil processing will be reduced to 60 kg/ton, which is 4.8% lower than that in 2017.	Comprehensive Emission Standards of Regional Air Pollutants in Shandong Province (Shandong Environmental Protection Department, 2013)
	Coal mining industry	Eliminate backward production capacity		List of Coal Mines with Backward Productivity in Shandong Province in 2015 (Shandong Coal Industry Bureau, 2017),
	other	Establishment of strict industrial emission standards		Comprehensive Emission Standards of Regional Air Pollutants in Shandong Province (Shandong Environmental Protection Department, 2013)
			By 2017, the intensity of atmospheric pollutant discharge in iron and steel, cement, and chemical industries, petrochemical industry, non-ferrous metal smelting, and other industries will be more than 30% lower than that in 2013.	Medium and Long-term Development Energy Plan of Shandong Province (Development and Reform Commission of Shandong Province, 2016)
Transportation	port terminal	New construction and extension of the terminal	New crude oil terminals (13), 38 oil and liquid chemical terminals, and 3 LNG terminals	Planning and Construction Plan for Oil and Gas Transportation Facilities in Shandong Province (2016–2020) (Shandong Development

		New construction and expansion of tank farms	New construction and expansion of tank farms	and Reform Commission, Shandong Economic and Information Commission, Shandong Transportation Department, 2015)
Resident	loose coal burning for winter	Increasing heating popularization rate	By 2020, the popularization rate of central heating [1] in urban areas reached more than 80%, and the household heating rate of distributed renewable energy [2] in rural areas reached more than 50%.	Medium and Long-term Development Energy Plan of Shandong Province (Development and Reform Commission of Shandong Province, 2016)
		Coal to gas	By 2017, 7 transmission channel cities completed more than 50,000 gas-to-coal or electric-generation coal projects, and strive to reduce coal consumption by 1 million tons.	Clean Coal Treatment Work Plan of Shandong Province (People's Government of Shandong Province, 2016)

[1] The central heating system is driven by large-capacity boilers in heating stations and power plants. The popularization rate of central heating means the utilization rate of the central heating system. Central heating is different from individual heating. [2] The distributed renewable energy system means fuel cleaning projects such as biomass cogeneration, biomass heating, large-scale biomass natural gas generation, methane-generating pit, and photovoltaic power station.

2.4. Modeling Configuration

The WRF model is a new-generation mesoscale numerical weather prediction model and assimilation system. The CAMx model is a third-generation air quality model based on the "one atmosphere" framework that can comprehensively simulate the distribution of gaseous and particulate atmospheric pollutants in cities and regions. PSAT is an important extension module of CAMx for particulate matter source analysis for specific source areas and emission sources [63]. This study used WRF v3.9.1 to simulate the 2015 regional meteorological field and provided hourly weather input data to CAMx. Then, CAMx v6.4 and the extension module PSAT were used to simulate the situation of Shandong Province in 2015, as well as the distribution of the concentrations of major atmospheric pollutants and the contributions of key energy-related industries to particulate matter concentrations under 2020 emission scenario [64]. January, April, July, and October were simulated to represent winter, spring, summer, and fall, respectively, to reflect seasonal variations of atmospheric pollutant concentrations. In order to make the emission reduction scenario simulation comparable to the base year, the meteorological field of the base year (2015) was used in the 2020 simulations and the model parameter settings were kept consistent with those of the baseline year simulation.

As shown in Figure 1, CAMx simulations are performed over three domains. Domain 1 covers the North China region with a resolution of 36 × 36 km, Domain 2 covers Shandong Province and part of the Beijing–Tianjin–Hebei region with a resolution of 12 × 12 km, and Domain 3 covers Shandong Province with a resolution of 4 × 4 km. In the simulation area, the Shandong Province area in the third grid layer relied on the emission inventory we developed. The other areas relied on the 2012 MEIC emission inventory developed by Tsinghua University [61].

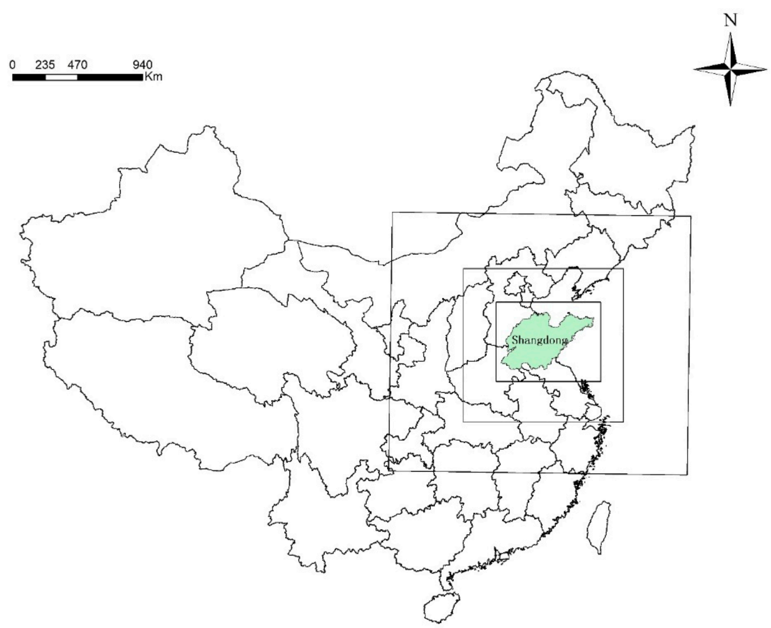


Figure 1. Model domain setting.

Many studies have shown that $PM_{2.5}$ mainly originates from local coal-fired power plants, steel, and transportation [65–68]. Therefore, to study the contributions of energy-consumption-related pollution sources to the particulate matter concentrations, especially pollution sources related to coal burning, 12 emission sources were set up in the PSAT module (Table 3.)

Table 3. Emission source settings in CAMx-PSAT.

Category	Sub-Category	Emission Source
Industry	key energy-related industries	thermal power
		steel
		chemical
		coking
		oil refining
		other key energy-related industries
	other industries	
Resident	urban residents	
	rural (suburban) residents	cooking in rural regions
		loose coal burning for winter heating
Transportation	--	--
Agriculture	--	--

3. Results and Discussion

3.1. Base Year Emission Inventory, and 2020 Emission Reduction Scenario

3.1.1. Base Year Emission Inventory

Table 4 and Figure 2 show the emissions of the main atmospheric pollutants in Shandong Province in 2015. As can be seen from the table, the emissions of SO_2, NO_X, CO, $PM_{2.5}$, PM_{10}, VOCs, and NH_3 were approximately 1.61, 1.46, 24.20, 0.548, 0.80, 1.33, and 0.663 million t, respectively. The industry contributed more than 65% of the SO_2, NO_X, CO, $PM_{2.5}$, PM_{10}, and VOCs emissions. The NH_3 emissions originated mainly from agriculture, accounting for up to 98%. The key energy-related industries emitted more than 55% of SO_2, NO_X, CO, $PM_{2.5}$, PM_{10}, and VOCs. These are the industries that need to be focused on when controlling air pollution in Shandong Province.

Table 4. The main atmospheric pollutant emissions in Shandong Province in 2015.

Category	Sub-Category	SO_2/t	NO_X/t	CO/t	$PM_{2.5}$/t	PM_{10}/t	VOCs/t	NH_3/t
Industry	key energy-related industries	1,014,818	839,896	19,162,557	392,285	577,612	894,272	4,511
	other industries	206,136	107,915	13,254	10,351	22,295	6,082	307
	total	1,220,954	947,811	19,175,811	402,636	599,907	900,354	4,818
Resident	urban residents	304,515	71,517	279,315	13,398	18,781	4,829	3,115
	rural (suburban) residents [1]	63,312	37,994	3,023,006	72,663	117,052	50,676	162
	among：loose coal burning for winter heating	21,885	11,195	948,786	31,912	41,020	19,472	0
	total	367,827	109,511	3,302,321	86,061	135,833	55,505	3,277
Transportation	on-road mobile	23,155	405,839	1,722,778	57,703	59,065	180,837	2,551
	road dust	0	0	0	1,399	5,504	0	0
	port terminal VOCs emission	0	0	0	0	0	191,483	0
	total	23,155	405,839	1,722,778	59,102	64,569	372,320	2,551
Agriculture		0	0	0	0	0	0	652,291

Total		1,611,936	1,463,161	24,200,910	547,799	800,309	1,328,179	662,937

[1] "Rural (suburban) residents" living emissions include those from cooking and loose coal burning for winter heating. Because loose coal burning for winter heating is one of the main causes for the heavy pollution in this season in Northern China, this study classified loose coal burning emissions for the winter heating as an independent pollution source category in PSAT and studied its contribution to the concentration of particulate matter. Therefore, its emissions are listed separately in Table 4.

3.1.2. Emission Inventories for 2020 Emission Reduction Scenario

Table 5 shows the main atmospheric pollutant emissions in Shandong Province in the 2020 emission reduction scenario. In the 2020 emission reduction scenario, the emissions of SO_2, NO_X, CO, $PM_{2.5}$, and PM_{10} all decreased significantly, mainly due to the reduction in emissions from key energy-related industries. The emissions of SO_2 and NO_X from key energy-related industries were 56% and 55% lower than those in 2015, respectively. The thermal power industry exhibited the largest reduction. This was mainly caused by the energy conservation and emission reduction measures, such as "eliminating backward production capacity", "raising pollutant emission standards", and "promoting clean coal use" in these industries.

Table 5. The main atmospheric pollutant emissions in Shandong Province in the 2020 emission reduction scenario.

Category.	**Sub-category**	**SO_2/t**	**NO_X/t**	**CO/t**	**$PM_{2.5}$/t**	**PM_{10}/t**	**VOCs/t**	**NH_3/t**
Industry	key energy-related industries	442,991	378,865	12,666,057	182,330	314,964	643,681	4,157
	other industries	118,524	65,163	9,277	7,773	16,648	10,902	216
	total	561,515	444,028	12,675,334	190,103	331,612	654,583	4,373
Resident	urban residents	306,718	72,633	278,513	13,360	18,727	4,816	3,106
	rural (suburban) residents [1]	22,048	16,933	1,264,369	19,023	47,315	14,963	162
	among：loose coal burning for winter heating	9,899	5,052	424,982	14,432	18,620	8,853	0
	total	328,766	89,566	1,542,882	32,383	66,042	19,779	3,268
Transportation	on-road mobile	23,155	405,839	1,722,778	57,703	59,065	180,837	2,551
	road dust	0	0	0	1,294	5,349	0	0
	port terminal VOCs emission	0	0	0	0	0	467,428	0
	total	23,155	405,839	1,722,778	58,997	64,414	648,265	2,551
Agriculture		0	0	0	0	0	0	652,291
Total		913,436	939,433	15,940,994	281,483	462,068	1,322,627	662,483

[1] The same as in Table 4.

3.2. *Model Verification*

3.2.1. Statistical Performance of Meteorological Variable Prediction

Observation data from 27 meteorology stations in Shandong Province were used in our evaluation. Figure 2 shows the location of meteorological monitoring sites. Table 6 presents the evaluation (27 stations on average) of wind speed, wind direction, 2-m temperature, and humidity as simulated by WRF and shows the recommended values for the above statistical quantities provided by the study of Emery et al. [69]. Model performance statistics include mean bias (MB), mean absolute gross error (MAGE), root mean square error (RMSE), correlation coefficient (r) and index of agreement (IOA). The statistical quantities in this study fall within the recommended range, indicating that the simulation error is small, and the results of the simulation are acceptable. The time series comparison between the simulation and the observations of wind speed, wind direction, 2-m temperature, and humidity are shown in Figure 3.

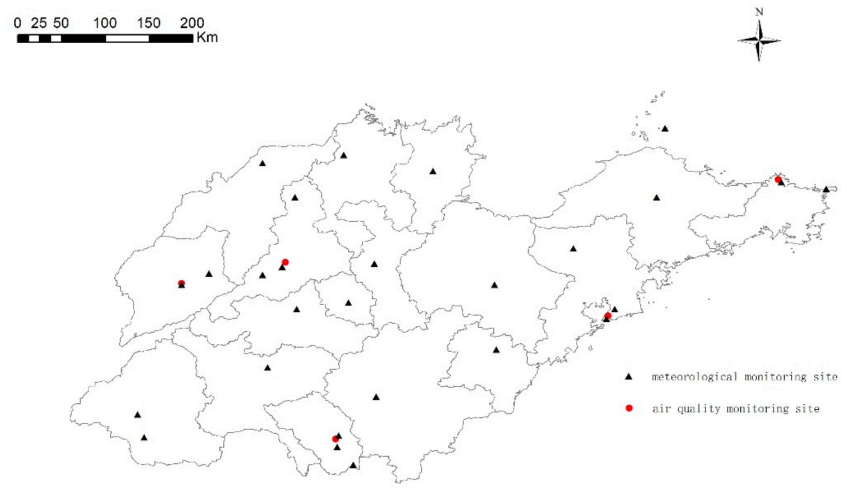


Figure 2. The location of meteorological monitoring sites and air quality monitoring sites.

Table 6. The evaluation of hourly Weather Research Forecast (WRF) meteorology simulation and recommended values.

Variables	MB	MAGE	RMSE	IOA	r
Wind speed	–0.06m/s (≤ ±0.5m/s)	-	0.95m/s (≤2m/s)	0.56 (≥0.6)	0.61
Wind direction	3.10deg (≤ ±10deg)	46.84deg (≤30deg)	-	-	0.63
Temperature(2m)	0.34K (≤ ±0.5K)	1.54K (≤2K)	-	0.74 (≥0.8)	0.81
Humidity	–0.92g/kg (≤ ±1g/kg)	0.95g/kg (≤2g/kg)	-	0.82 (≥0.6)	0.83

Note: a) the data in the brackets indicate the corresponding recommended values for statistical quantities of meteorological parameters from the study of Emery et al. [69]; b) deducting the missing value, the numbers of the observation-measurement pairs used were 2921, 2898, 2887, and 2906 for wind speed, wind direction, temperature, and humidity, respectively.

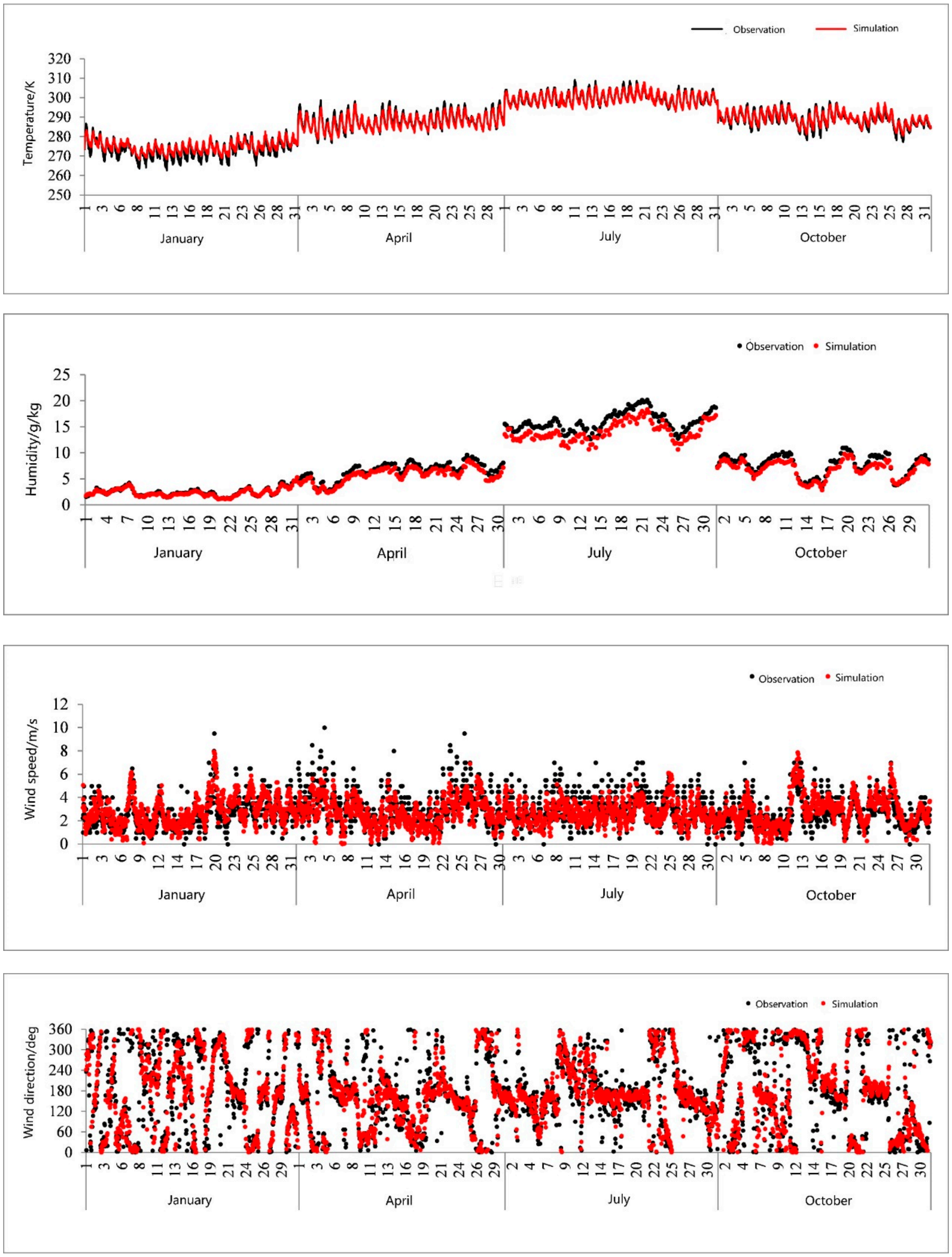


Figure 3. Model and observation comparison for 27 stations in Shandong province: (**a**) temperature; (**b**) humidity; (**c**) wind speed; (**b**) wind direction.

3.2.2. Statistical Performance of Air Pollutant Predictions

For the assessment of the effect of pollutant concentrations in the simulation, five provincial monitoring stations in Shandong Province were selected, including the Jinan (JN), Qingdao (QD), Liaocheng (LC), Zaozhuang (ZZ), and Weihai (WH) stations, as representatives of different locations across the province. The location of the air quality monitoring sites is shown in Figure 3. The observation data used for the assessment were the daily averages of five types of pollutants from these stations in January, April, July, and October of 2015. The model evaluation statistics matrix for the CAMx results for SO_2, NO_2, $PM_{2.5}$, and PM_{10} is shown in Table 7; Table 8.

In general, the overall simulation results of the five pollutants were good. By comparing the average simulation value and the observation value of the province in 2015, it can be seen that the overall simulated values were systematically lower. The values of SO_2, NO_2, $PM_{2.5}$, and PM_{10} were lower by 12.3%, 38.6%, 9.4%, and 41.6%, respectively. There are three reasons that could cause errors in the simulation: (1) the uncertainty of the source inventory. The relatively low PM_{10} concentration in the simulation could be related to the fact that the dust in the stack was considered in the emission inventory, and the emission from the road dust sources in the MEIC inventory was low; (2) errors in the meteorological field simulation; (3) theoretical flaws in the model, since the model simulation value is the average of the pollutant concentration in the 4-km grid, which caused the simulation value to be low. The atmospheric chemical reaction mechanism used in the model is also a possible source of error.

Table 7. Performance statistics for hourly pollutant concentrations.

Pollutant	Station	JN	QD	LC	ZZ	WH	Average
SO_2 (μg/m^3)	MB	−4.6	−10.3	−2	−11.9	2.6	−5.3
	MAGE	5.6	11.2	3.4	12.8	3.6	7.3
	RMSE	8.3	14.8	8.8	15.6	7.8	11.1
	IOA	0.73	0.68	0.71	0.75	0.74	0.72
	r	0.72	0.73	0.74	0.72	0.68	0.72
NO_2 (μg/m^3)	MB	−19	−19.7	−10.4	−16.9	−15.4	−16.3
	MAGE	21.2	20.8	12.4	18.8	17.1	18.1
	RMSE	28	32.2	12.4	18.9	17.3	21.8
	IOA	0.58	0.56	0.66	0.62	0.61	0.61
	r	0.59	0.58	0.63	0.63	0.59	0.6
$PM_{2.5}$ (μg/m^3)	MB	−6.3	−6.6	−8	−6.3	−5.9	−6.6
	MAGE	7.2	8.9	10.8	8.1	7.4	8.5
	RMSE	16.9	13.6	12.4	10.4	11.7	13
	IOA	0.76	0.72	0.71	0.78	0.81	0.76
	r	0.74	0.75	0.73	0.72	0.76	0.74
PM_{10} (μg/m^3)	MB	−76.7	−30	−70	−72.6	−21.8	−54.2
	MAGE	77.1	32.1	71.7	74.1	22.6	55.5
	RMSE	78.8	34.6	73.3	75.2	24.4	57.3
	IOA	0.42	0.54	0.44	0.41	0.54	0.47
	r	0.43	0.52	0.45	0.42	0.53	0.47

Note: deducting the missing value, the numbers of hourly observation-measurement pairs used were 2901, 2932, 2886, and 2898 for SO_2, NO_2, $PM_{2.5}$, and PM_{10} of the Jinan (JN) station, respectively; the numbers of hourly observation-measurement pairs used were 2898, 2932, 2901, and 2905 for SO_2, NO_2, $PM_{2.5}$, and PM_{10} of the Qingdao (QD) station, respectively; the numbers of hourly observation-measurement pairs used were 2899, 2924, 2903, and 2922 for SO_2, NO_2, $PM_{2.5}$, and PM_{10} of the Liaocheng (LC) station, respectively; the numbers of hourly observation-measurement pairs used were 2899, 2913, 2903, and 2909 for SO_2, NO_2, $PM_{2.5}$, and PM_{10} of the Zaozhuang (ZZ) station, respectively; the numbers of hourly observation-measurement pairs used were 2895, 2911, 2923, and 2908 for SO_2, NO_2, $PM_{2.5}$, and PM_{10} of the Weihai (WH) station, respectively.

Table 8. The diurnals of simulated and observed air pollutants concentrations.

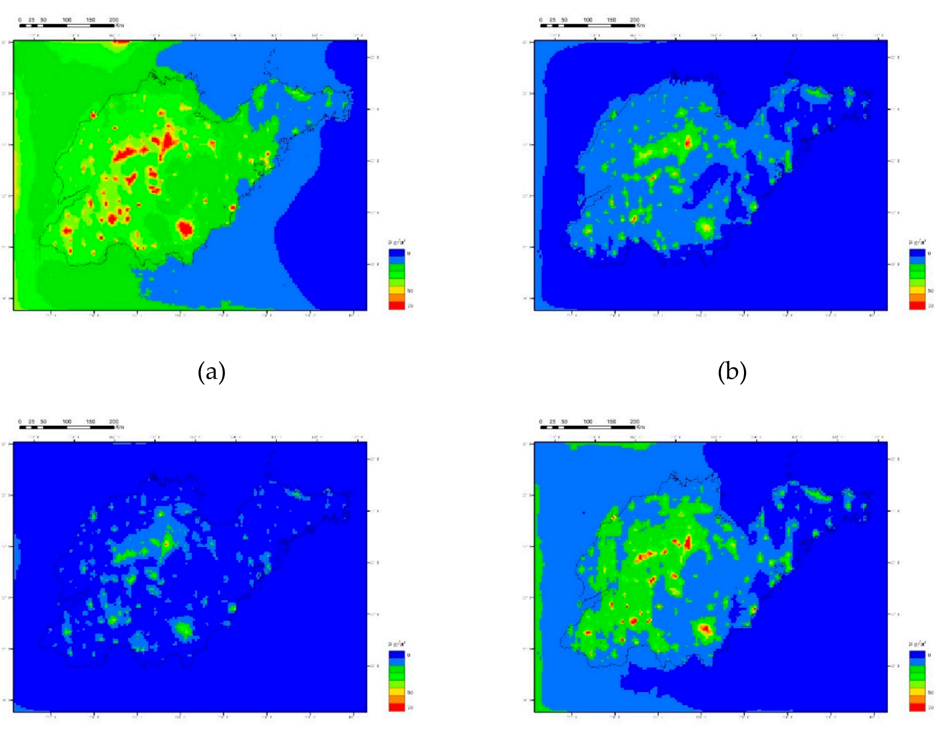
Station	SO_2 (μg/m³)		NO_2 (μg/m³)		$PM_{2.5}$ (μg/m³)		PM_{10} (μg/m³)	
	Obs_{mean}	Sim_{mean}	Obs_{mean}	Sim_{mean}	Obs_{mean}	Sim_{mean}	Obs_{mean}	Sim_{mean}
JN	57	52	62	43	93	87	159	82
QD	27	17	36	16	55	48	92	62
LC	50	48	41	31	98	90	168	98
ZZ	72	60	38	22	90	84	165	92
WH	17	20	30	14	42	36	70	48
Average	45	39.5	41	25.2	76	68.9	131	76.5

Note: the number of the daily observation-measurement pairs used was 123 for SO_2, NO_2, $PM_{2.5}$, and PM_{10} of JN, QD, LC, ZZ, and WH stations.

3.3. Results of the Simulation of the Base Year

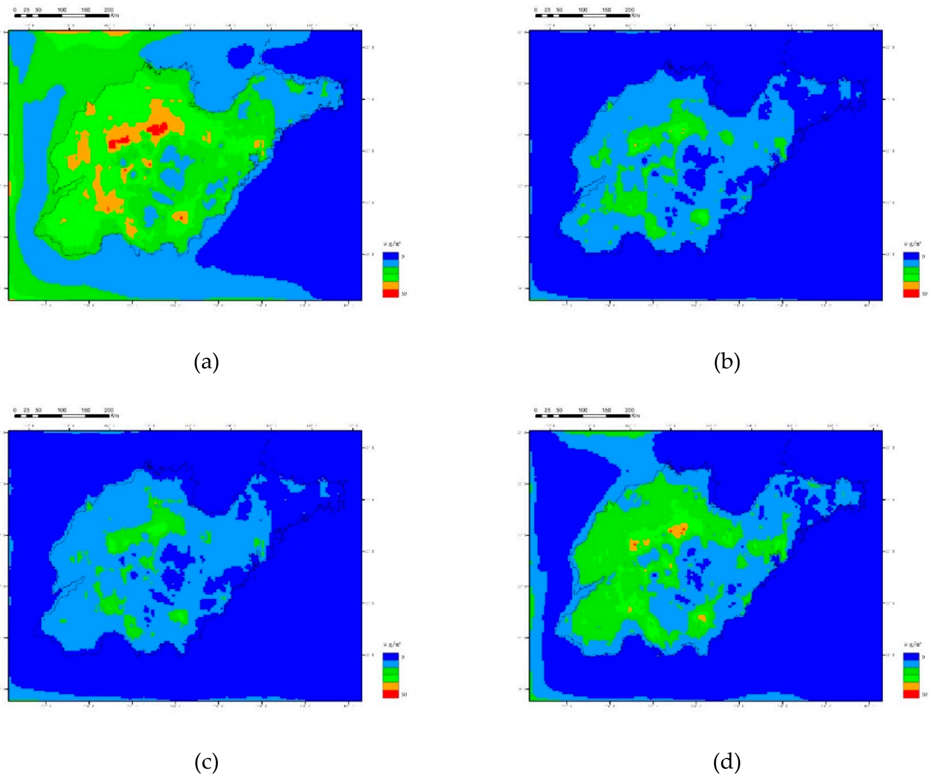
3.3.1. Distribution Characteristics of Atmospheric Pollutants in Different Seasons

The simulated concentration fields of SO_2, NO_2, $PM_{2.5}$, and PM_{10} exhibited obviously spatial and seasonal variations. The spatial distribution of SO_2, NO_2, $PM_{2.5}$, and PM_{10} presented a characteristic of "high in the west and low in the east". This phenomenon is related to the horizontal diffusion of pollutants, meteorological conditions, and land and sea differences of the underlying surface [70,71]. The eastern coastal areas of Shandong Province are perennially affected by the oceans. Boundary layer processes, such as the sea–land breeze circulation, affect the spatial distribution, transport, diffusion, and accumulation of pollutants [72–74]. In general, these processes produce meteorological conditions that are conducive to the diffusion and dilution of pollutants. The concentrations in winter were significantly higher than in the other seasons, which was consistent with the seasonal trend of monitoring data (Figure 4 Figure 5 Figure 6 Figure 7). The seasonal variation pattern is similar to that of many regions in China [75–79].



(a) (b) (c) (d)

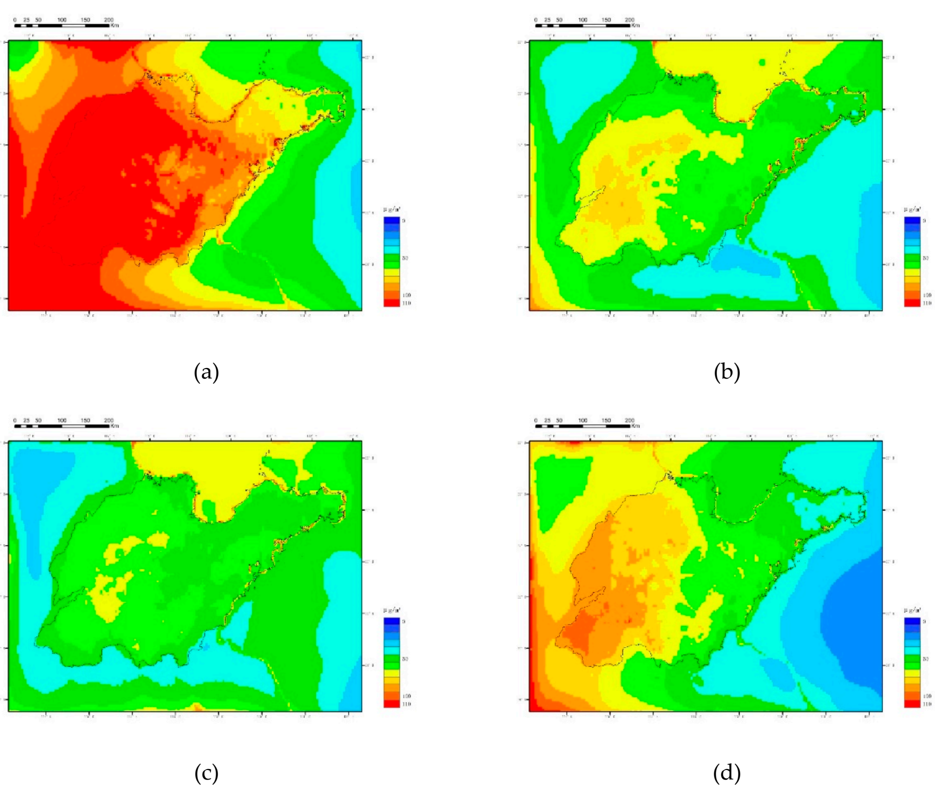
Figure 4. Simulated concentration of SO_2（μg/m³）in (**a**) January 2015, (**b**) April 2015, (**c**) July 2015, (**d**) October 2015.



(a) (b)

(c) (d)

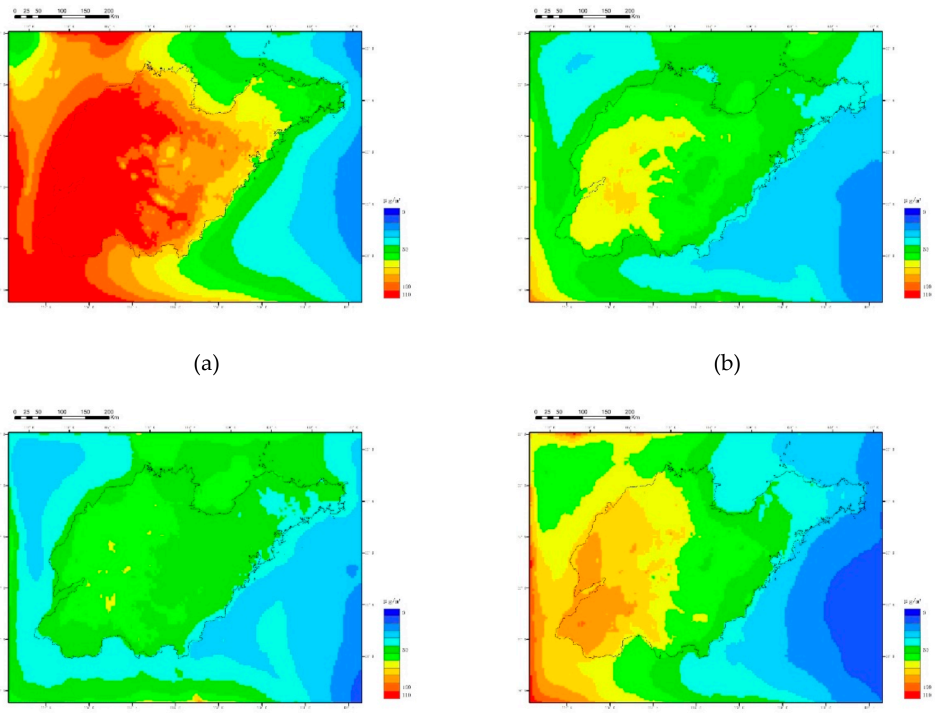
Figure 5. Simulated concentration of NO_2（μg/m^3）in (**a**) January 2015, (**b**) April 2015, (**c**) July 2015, (**d**) October 2015.



(a) (b)

(c) (d)

Figure 6. Simulated concentration of PM_{10} ($\mu g/m^3$) in (**a**) January 2015, (**b**) April 2015, (**c**) July 2015, (**d**) October 2015.



(a) (b)

(c) (d)

Figure 7. Simulated concentration of $PM_{2.5}$ ($\mu g/m^3$) in (**a**) January 2015, (**b**) April 2015, (**c**) July 2015, (**d**) October 2015.

3.3.2. Sources Analysis of Fine Particulate Matter in Shandong Province

Table 9 shows the average contributions and the percentage of each sector contribution in January, April, July, and October. Overall, the major contributions were industry, residents, and transportation. Their average contributions were 34.7%, 26.3%, and 15.2%, respectively, and industry was the largest contributor. The average contribution of agriculture was 7.3%, revealing that ammonia emitted from agriculture can chemically react with gaseous pollutants, such as SO_2 and NO_X, to form ammonium sulfate and ammonium nitrate, which are important precursors of fine particulate matter ($PM_{2.5}$) [80–82].

The contribution of various sources presented seasonal variations. The contribution of residents was the most highest in January, and other sector's contributions were not the same. In April, July, and October, industry was the largest contributor, with 38.6%, 45.3%, and 31.4%, respectively. In January, the residents were the largest contributors, with 41.30%. Among them, the contribution of loose coal burning for winter heating was as high as 19.4%, indicating that loose coal burning was an important contributor to the fine particulate matter pollution in January. As of 2016, a quarter of rural areas in Shandong Province still used traditional methods, such as loose coal and wood burning, for activities such as cooking, heating, and water boiling [62,83]. The amount of pollutants emitted by loose coal burning was very large, and the emissions occur near the ground. The unit emission contribution to air pollution was much higher than that of high-altitude emission sources [84]. Therefore, loose coal combustion has been identified as an important contributor to severe particulate matter pollution [70,85–89]. It can be seen that the use of strong and comprehensive measures to control the burning of loose coal is also an important way to address air pollution in the study area [84,90].

Table 9. The average source contributions to $PM_{2.5}$ concentration and the percentage of each sector contribution in January, April, July, and October in Shandong Province in the base year.

Category	Sub-category	January	April	July	October	Average [2]
Industry	key energy-related industries	18.40%	33.90%	39.60%	26.20%	29.50%
	other industries	5.10%	4.70%	5.60%	5.20%	5.20%
	total	23.50%	38.60%	45.30%	31.40%	34.70%
Resident	urban residents	13.00%	15.90%	11.30%	17.60%	14.50%
	rural (suburban) residents	28.30%	5.60%	4.90%	8.30%	11.80%
	Among: loose coal burning for winter heating	19.40%	0.00%	0.00%	0.00%	4.90%
	total	41.30%	21.70%	16.20%	25.90%	26.30%
Transportation		13.30%	16.10%	13.50%	17.70%	15.20%
	Agriculture	5.30%	8.70%	6.90%	8.30%	7.30%
	Outside [1]	16.60%	14.90%	18.20%	16.70%	16.60%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

[1] "Outside" refers to the pollution sources of non-Shandong Province in the third grid. [2] "Average" refers to the average value of January, April, July, and October.

Table 10 shows the average contributions and the percentage of each sector contribution in January, April, July, and October within the key energy-related industries' contributions. Their cumulative average contribution reached 29.5%; they were the largest contributor among the industry.

Most of the key energy-related industries mainly rely on coal-fired power generation, and this is particularly true for the thermal power industry. The emission of fine particulate matter from the thermal power industry accounts for 14% of the total emission of fine particulate matter. The average contribution of the thermal power industry reached 20.4%, which indicated that the thermal power industry had a direct contribution to fine particulate matter [91]. Also, gaseous pollutants such as SO_2 and NO_X emitted by the thermal power industry can form secondary sulfates and nitrates through chemical reactions, which become an important component of the secondary fine particulate matter [92–97]. Therefore, the introduction of a more stringent thermal pollution control policy is an important aspect for improving the quality of the atmospheric environment in Shandong Province.

Table 10. The average contribution of key energy-related industries to $PM_{2.5}$ concentration and the percentage of each sector contribution in January, April, July, and October in the base year.

Category	January	April	July	October	Average [1]
Thermal Power	12.80%	24.20%	27.00%	17.60%	20.40%
Steel	2.30%	4.00%	5.10%	3.40%	3.70%
Chemical	1.30%	3.10%	4.00%	2.70%	2.80%
Oil Refining	0.30%	1.00%	1.30%	0.90%	0.80%
Other Key Energy-Related Industries	0.60%	0.50%	0.60%	0.60%	0.60%
Total	18.40%	33.90%	39.60%	26.20%	29.50%

[1] "Average" refers to the average value of January, April, July, and October.

3.4. Source Analysis of Fine Particulate Matter in the 2020 Emission Reduction Scenario

Based on the simulation of the base year, the 2020 emission reduction scenario simulation was made. The temporal and spatial variation characteristics of pollutant concentration in the 2020 emission reduction scenario are consistent with that in 2015. Table 11 shows the average contributions and the percentage of each sector contribution in January, April, July, and October for the 2020 emission reduction scenario. Overall, the extraterritorial pollution source was the largest contributor, with values as high as 49.9%. This is related to the fact that the emission reduction of the extraterritorial pollution source was not considered in the scenario. This also indicates that even though Shandong Province implements relevant energy conservation and emission reduction policies and measures, if the atmospheric pollutant emissions from surrounding areas remain unchanged, the extraterritorial sources will become the primary pollution sources of fine particulate matter in Shandong Province. This also reflects, to a certain extent, that the control of environmental air pollution must be performed jointly by adjacent regions.

In the 2020 scenario, industries have become the second largest contributor. Their average contribution was 17.18%, showing a decrease of 17.52% compared to 2015. This indicates that the emission reduction policies and measures of industries can be highly beneficial.

In the 2020 scenario, the average contribution of residents was 8.7%, showing a decrease of 17.6% compared to 2015. In January, the residents were no longer the largest contributors, with 13.19%. Among them, the contribution from winter loose coal burning in January was 6.03%, showing a decrease of 13.37% compared to 2015. This indicates that the implementation of emission reduction measures on residents have a significant effect on reducing the concentration of fine particulate matter. Particularly effective should be the emission reduction measures for loose coal burning in the heating seasons, such as promoting the "coal-to-gas" project, increasing the penetration rate of central heating, and others.

In the 2020 scenario, the average contribution of transportation was 8.11%, showing a decrease of 7.09% compared to 2015. On the other hand, the average contribution of agriculture is 16.1%, showing an increase of 8.8% compared to 2015. This could be due to the fact that the emission reduction policies and measures of agriculture are not considered in the 2020 scenario. In case where the emissions from industry reduce significantly, the contribution rate of agriculture to pollutant concentrations will show a relative increase.

Table 11. The average source contributions to $PM_{2.5}$ concentration and the percentage of each sector contribution in January, April, July, and October in Shandong Province in the 2020 scenario.

Category	Sub-category	January	April	July	October	Average [2]
Industry	key energy-related industries	13.39%	13.80%	17.40%	12.52%	14.28%
	other industries	2.91%	2.94%	2.95%	2.82%	2.91%
	total	16.29%	16.74%	20.36%	15.34%	17.18%
Resident	urban residents	5.75%	5.43%	7.11%	5.48%	5.94%
	rural (suburban) residents	7.44%	1.07%	1.18%	1.32%	2.75%
	among: loose coal burning for winter heating	6.03%	0.00%	0.00%	0.00%	1.51%
	total	13.19%	6.50%	8.29%	6.80%	8.69%
Transportation		7.63%	8.31%	8.30%	8.21%	8.11%
	Agriculture	15.22%	22.20%	13.06%	13.94%	16.10%
	Outside [1]	47.67%	46.26%	49.99%	55.70%	49.90%
Total		100%	100%	100%	100%	100.00%

[1] "Outside" refers to the pollution sources of non-Shandong Province in the third grid. [2] "Average" refers to the average value of January, April, July, and October.

Table 12 shows the average contributions and the percentage of each sector contribution in January, April, July, and October within the key energy-related industries' contributions in the 2020 emission reduction scenario. Their average contribution was 14.28%, showing a decrease of 15.22% with respect to 2015. However, these industries were still the largest contributors among all the industries. On the other hand, in the 2020 scenario, the thermal power industry was no longer the largest contributor; its average contribution was only 1.75%, showing a decrease of 18.65% with respect to 2015. On the other hand, other key energy-related industries had become the largest pollution sources with their cumulative contribution being 8.7%, showing an increase of 8.1% with respect to 2015. This may be related to the fact that the 2020 scenario mainly focuses on energy conservation and emission reduction in the thermal power industry, which results in the relative increase in the emission proportion of atmospheric pollutants from the other key energy-related industries.

Table 12. The average contribution of key energy-related industries to $PM_{2.5}$ concentration and the percentage of each sector contribution in January, April, July, and October in the 2020 scenario.

Category	January	April	July	October	Average [1]
thermal power	1.62%	1.82%	2.06%	1.49%	1.75%
steel	0.85%	0.72%	0.87%	0.68%	0.78%
chemical	1.58%	1.73%	2.00%	1.45%	1.69%
coking	0.42%	0.46%	0.71%	0.42%	0.50%
oil refining	0.72%	0.85%	1.12%	0.73%	0.86%
other key energy-related industries	8.19%	8.21%	10.65%	7.76%	8.70%
total	13.39%	13.80%	17.40%	12.52%	14.28%

[1] "Average" refers to the average value of January, April, July, and October.

3.5. The Improving Effect of Control Policies on the Air Pollution Situation in Shandong Province under the 2020 Emission Reduction Scenario

As can be seen from Table 13, the 2020 emission reduction scenario has been significantly reduced compared with the base year (2015) in terms of major gaseous pollutants (SO_2, NO_X, CO) and primary particulate matter ($PM_{2.5}$, PM_{10}), with a reduction rate of more than 30% while the reduction rates of VOC and NH_3 are minimal. Under such a emission reduction scenario, the average concentrations of SO_2, NO_X, $PM_{2.5}$, and PM_{10} decreased by 30%, 24%, 46%, and 46%, respectively (Table 14). The decrease rates of SO_2 and NO_X in October were the largest, reaching 42% and 29%, respectively; the decrease rate of $PM_{2.5}$ and PM_{10} in July was the largest, reaching 49% and 48%, respectively. Thus it can be seen that under the background of heavy pollution in Shandong Province, the reduction of primary particulate matter emissions and SO_2, NO_X, and other gaseous pollutants have a direct and significant improvement on reducing particulate matter concentrations.

The results show that the reduction rate of gaseous pollutants (SO_2, NO_X) emissions was slightly less than the decrease rate of the average concentration of gaseous pollutants. The reduction ratios of particulate matter emission are consistent with the decrease ratios of the average concentration of particulate matter.

Table 13. Emissions and reduction rates of major air pollutants comparing the 2020 emission reduction scenario with the base year in Shandong Province.

Pollutant	Average Emissions(kt)		Reduction Rates
	Base Year	2020	2020
SO_2	1611.94	913.44	43%
NO_2	1463.16	939.43	36%
$PM_{2.5}$	547.8	281.48	42%
PM_{10}	800.31	462.07	49%
VOCs	1328.18	1322.63	0.40%
NH_3	662.94	662.48	0.10%
CO	24,200.91	15,940.99	34%

Table 14. The major air pollutant concentration in January, April, July, and October, average concentrations of the above four months in 2015 and 2020, decrease rates of major air pollutants comparing the 2020 emission reduction scenario with the base year (2015) in Shandong Province.

Pollutant	Simulated Concentration [1] (μg/m³)						Decrease Rates [3]
	Year	January	April	July	October	Average [2]	
SO_2	2015	68.22	37.25	27.06	36.91	42.36	30%
	2020	46.45	29.58	20.41	21.45	29.47	
NO_2	2015	32.89	23.13	22.73	25.49	26.06	24%
	2020	25.12	18.65	17.32	17.98	19.77	
$PM_{2.5}$	2015	103.35	66.97	53.49	72.80	74.15	46%
	2020	56.82	36.49	27.14	39.56	40.00	
PM_{10}	2015	105.43	72.59	68.78	82.81	82.40	46%
	2020	58.36	39.21	35.69	46.07	44.83	

[1] In this paper and this table, the simulated concentration of pollutants in the whole Shandong Province is represented by the average concentration of pollutants in all simulation grids in space (spatial average). [2] "Average" refers to the average value of January, April, July, and October. [3] "Decrease rates" refers to the reduction rate of the average value of January, April, July, and October comparing the 2020 emission reduction scenario with the base year.

3.5.1. Policies and Measures for Reducing the Emissions from Industry

In 2015, industry was the largest contributor of fine particulate matter in Shandong Province. Accelerating energy conservation and emission reduction in the industrial sector is an important way to reduce the pollution of atmospheric particulate matter in Shandong Province.

As can be seen from Table 5, in the 2020 emission reduction scenario, the emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10} from industry are estimated to be approximately 561 kt, 444 kt, 190 kt, and 331.6 kt, respectively. Compared to the data in Table 4, the above-mentioned pollutants were reduced by 54%, 53%, 53%, and 45%. These are the type of pollution sources with the largest emission reduction in the 2020 emission reduction scenario. Especially for the key energy-related industries, the emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10} are reduced by more than one-third compared to 2015. The reduction of SO_2, NO_X, $PM_{2.5}$, and PM_{10} from key energy-related industries, respectively, accounted for 82%, 88%, 79%, and 78% of the total reduction of SO_2, NO_X, $PM_{2.5}$, and PM_{10}. The 2020 scenario also predicts a reduction by more than 20%, compared to 2015, of the average concentrations of SO_2, NO_2, PM_{10}, and $PM_{2.5}$. Among them, the average concentrations of $PM_{2.5}$ and PM_{10} are both reduced by 46%. With respect to the $PM_{2.5}$, the contribution from industry decreased by 17.52%, while the contribution from key energy-related industries decreased by 15.22% and the contribution from the thermal power industry decreased by 18.65%. This indicates that the strict implementation of control policies and measures, such as "energy conservation and emission reduction", "increasing the establishment threshold of high energy consumption industrial project", and "eliminating backward production capacity" by industry (especially the key energy-related industries) can significantly improve the air quality. In particular, the introduction of strict pollution control measures in the thermal power industry is an effective way to improve the quality of the atmospheric environment in Shandong. Examples of measures are as follows: "by 2020, the average coal consumption of active coal-fired generating units after renovation will be less than 310 g/kWh"; "raise the concentration emission standard of pollutant emissions (i.e., under the condition of reference oxygen content of 6%, the emission concentrations of smoke and dust, SO_2, NO_X are no higher than 10, 35, 50 mg/m³, respectively)"; "the proportion of coal in primary energy consumption drops to below 62%"; "new coal-fired power generation projects should use ultra-supercritical unit of 600,000 kilowatts and above"; "eliminate conventional small thermal power units with stand-alone capacity of 50,000 kilowatts or less, fuel boilers mainly for power generation, and generator sets". In the foreseeable future, coal will continue to be the main energy source for industries in Shandong Province. Clean and efficient use of coal is an effective way to implement energy conservation and emission reduction policies in Shandong Province. For traditional coal-fired power plants, building large units to replace the original small ones is the policy with the best emission reduction effects. For existing coal-fired power plants, flue gas desulfurization equipment and the implementation of ultra-low emission technologies synergistically produce relatively good emission reduction effects [98].

3.5.2. Emission Reduction Policies and Measures for the Resident

In 2015, the resident contributed more than one-quarter to fine particulate matter in Shandong Province, and thus was a major contributor to particulate matter pollution. It can be seen that strengthening the energy conservation and emission reduction and control of resident are also important aspects of air pollution control, particularly that of fine particulate matter.

In the 2020 emission reduction scenario, the emission reduction potential of SO_2, NO_x, PM_{10}, and $PM_{2.5}$ from residents are only second to that of industry. In 2020, the emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10} from residents are 39 kt, 19.9 kt, 53.7 kt, and 69.8 kt, respectively. The above-mentioned pollutants were reduced by 11%, 18%, 62%, and 51% compared to 2015. At the same time, the average contribution of residents decreased by 17.6% compared to 2015. Among them, the contribution of emissions from winter heating loose coal burning decreased by more than 10%. This indicates that strengthening the energy conservation and emission reduction for residents is important for improving the air quality in Shandong Province, especially via reducing the particulate matter pollution. The reduction in emissions from loose coal burning is also conducive to improving the particulate pollution situation in winter. In order to achieve the goal of "green water and blue sky" in Shandong Province, the cleanliness of the energy structure for future residents' life should be continuously enhanced. The energy consumption pattern should be gradually transformed into "electricity-based, coal-supplemented" [99]. The winter clean heating project should be promoted, and coal-to-gas, coal to electricity, centralized heating, and other means to reduce dispersed and inefficient coal burning should be pursued [100].

4. Conclusions

The exploitation and use of fossil energy are closely related to the generation and emission of atmospheric pollutants. Therefore, the implementation of energy-related planning has a significant impact on the regional atmospheric environment. Taking the provincial-level energy development plan as an example, this study relied on a scenario analysis combined with an environmental air quality numerical model based on the "Medium- and Long-Term Energy Development Plan of Shandong Province" to investigate the atmospheric environmental effects of governmental energy conservation and emission reduction policies, programs, and plans.

Numerical simulations relative to the base year show that there were significant differences in spatial and seasonal variations in the main atmospheric pollutant concentrations in Shandong Province. The spatial distribution of SO_2, NO_2, $PM_{2.5}$, and PM_{10} presented the characteristics of "high in the west and low in the east" (i.e., higher concentration in the central and western regions and lower concentration in the eastern coastal areas). In terms of seasonal variations, the concentration of the above pollutants is lower in spring and summer, and higher in fall and winter.

In the base year, industries were the largest contributors to the fine particulate matter pollution in Shandong Province, contributing 34.7%, while the key energy-related industries contributed 29.5%. Among them, the thermal power industry had the largest individual contribution (20.4%), which was higher than that of other key energy-related industries. Residents were the largest contributor in January (40%). In particular, the emissions from loose coal burning for winter heating contributed up to 19.4% in January.

According to the 2020 emission reduction scenario, the overall environmental air quality in Shandong Province is expected to improve significantly. The average concentration of $PM_{2.5}$ should reduce from 74.15 $\mu g/m^3$ in 2015 to 40 $\mu g/m^3$ in 2020. It can be seen that energy conservation and emission reduction policies and measures implemented for industry and residents (particularly the emission reduction measures for key energy-related industries and loose coal burning for winter heating) can significantly reduce the emissions of SO_2, NO_X, $PM_{2.5}$, and PM_{10} and have a significant effect on reducing the average concentrations of these pollutants, thereby improving the air pollution situation in Shandong Province. In general, the greater the emission reduction, the greater the decrease in pollutant concentrations.

Finally, this paper also shows that scenario analysis is an important and effective means to carry out energy-related planning and atmospheric environment prediction and evaluation. The emission inventory for the 2020 emission reduction scenario in this paper is based on the baseline inventory. The middle- and long- term macro-policies, planning, and micro-emission reduction policies are implemented in different industries and enterprises. The emission inventory was developed by fully integrating macro-planning, policies, and micro-measures, which effectively reduces the uncertainty of the scenario analysis and the corresponding emission inventory. Therefore, the beneficial effect on the atmospheric environment quality after the implementation of energy planning and various government energy conservation and emission reduction policies can be predicted more effectively.

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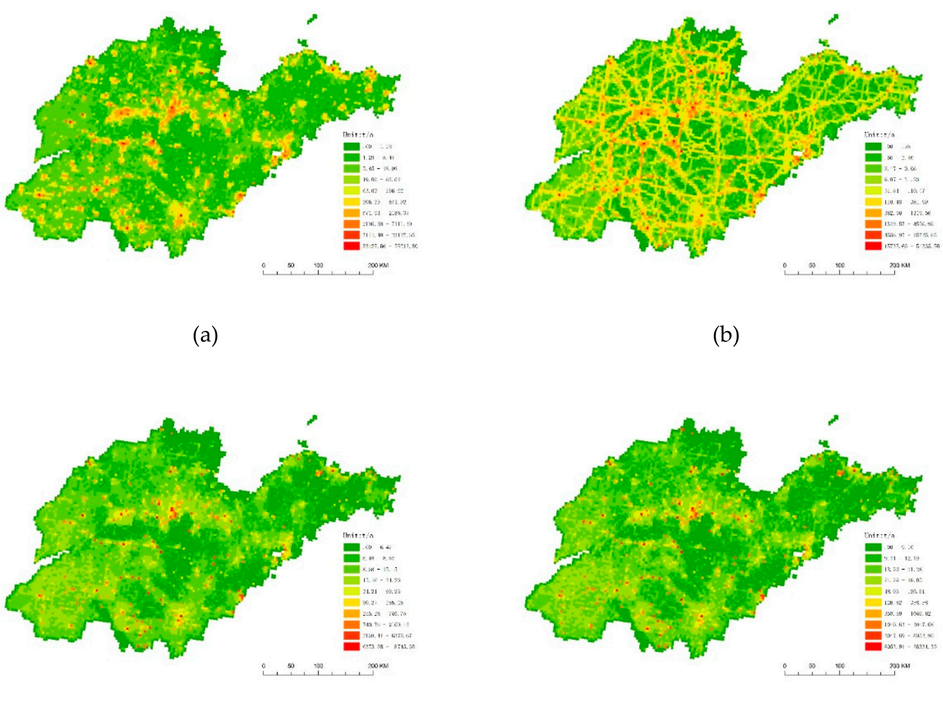
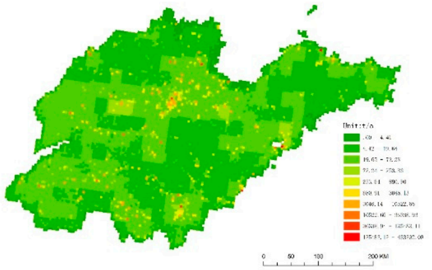
Appendix

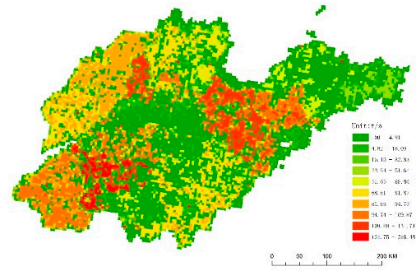


(a) (b)

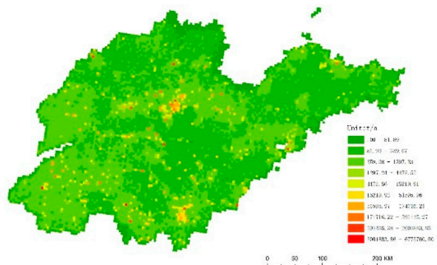
(c) (d)



(e)



(f)



(g)

Figure A1. The spatial distribution of major atmospheric pollutant emissions in Shandong Province in 2015: (**a**) SO_2; (**b**) NO_x; (**c**) $PM_{2.5}$; (**d**) PM_{10} (**e**) VOCs; (**f**) NH_3; (**g**) CO.

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