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What Are the Key Factors Affecting Air Pollution? Research on Jiangsu, China from the Perspective of Spatial Differentiation

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Abstract: Based on the spatial Dubin model, two representative atmospheric pollutants comprising industrial waste gas and NO_2 were selected to empirically investigate the effects of eight variables, including the economic growth level, population size, and industrial structure, on atmospheric pollutants and measure the sub-regional effects using data for Jiangsu from 2000 to 2016. The results showed that the population size, economic growth level, rural modernization level, personal income, and introducing high-speed rail were positively correlated with air pollution. By contrast, the industrial structure, foreign direct investment, and urbanization level were negatively correlated with air pollution. In particular, the effects of personal income, foreign direct investment, introducing high-speed rail, and urbanization were significant. The sub-regional analyses detected spatial spillover effects in all regions. The direct effects were greater than the indirect effects, where the level of economic growth, foreign direct investment, and urbanization had significant impacts, and the spatial spillover effects were most obvious in northern Jiangsu and central Jiangsu. Therefore, the following solutions are proposed: adjusting the industrial structure, improving the mode of economic growth, promoting the use of clean energy and rationally introducing foreign direct investment.

Keywords: atmospheric pollutant; Jiangsu Province; spatial Dubin model; spatial spillover effect

1. Introduction

China's economy has shifted from a high-speed growth stage to a high-quality development stage. Thus, China is in a process where the development mode is transforming by optimizing the economic structure and shifting the growth momentum. There is an urgent need to improve the efficiency of resource and energy utilization, decrease environmental pressure, and improve the air quality [1]. At present, China's energy consumption is effectively controlled. With the combined effects of controlling total coal, promoting the clean use of fossil energy, and vigorously developing non-fossil energy, the energy consumption structure has been further optimized. It was shown that non-fossil energy accounted for 13.8% of primary energy consumption in 2017, and the target completion degree was as high as 60%. With the dual effects of effective energy control and energy structure optimization, in 2017, total emissions of chemical oxygen demand (COD), total ammonia nitrogen (tan), sulfur dioxide (SO_2), and nitrogen oxides (NO_X) decreased by 5.6%, 6.4%, 13.2%, and 8.7%, respectively. The achievement of these results is closely related to China's active promulgation of a series of low-carbon and air pollution control policies in recent years. Environmental pollution is a severe problem that threatens the health of residents, and thus, air pollution should be addressed.

As one of the most developed provinces in China, Jiangsu Province is an important part of the Yangtze River Delta located in the middle of the eastern coast of mainland China, which has a more rapid economic growth rate and urbanization rate than the national average. In 2018, the urbanization rate of Jiangsu Province was 69.6%, while that of China was 60.6% [2]. However, the contradictory requirements for rapid economic and social development and the carrying capacity of resources and the environment in Jiangsu Province have become increasingly obvious. The energy structure is uniform, and the industrial structure is biased. Structural and regional environmental pollution are difficult to rectify, and many issues affect environmental protection. The problems that affect the ecological environment are major shortcomings that restrict the development of a thriving society in Jiangsu Province. The long-term "coal-type" energy structure, "heavy-type" industrial structure, and excess capacity in Jiangsu Province are difficult to change in the short term [3]. As a consequence, environmental air quality standards are also very poor. It was shown that the ambient air quality in 13 districts and cities did not meet the secondary standard in 2017. The environmental air quality compliance rate in Jiangsu Province was 68.0%, 2.2% lower than that in 2016 [4]. The concentrations of major pollutants comprising particulate matter (PM), SO_2, and carbon monoxide (CO) have decreased each year, but the concentrations of ozone and nitrogen dioxide (NO_2) have increased each year. The average annual concentration of $PM_{2.5}$ was 32.9% lower in 2017 compared with 2013, thereby exceeding the target requirement of "20% lower than 2013" in the national "Atmosphere Ten," but the PM, ozone (O_3), and NO_2 levels were still high in 13 districts and cities. Generally speaking, NO_2 mainly derives from the combustion of fuel and automobile exhaust, which mainly refers to urbanization, and industrial processes are the main cause of industrial exhaust emissions. Considering the rapid development of urbanization and industrialization, analyzing the factors that influence air pollution in Jiangsu Province can provide a reference to facilitate government actions to improve the atmospheric conditions and promote sustainable economic development. Therefore, referring to the spatiotemporal nature of air pollution, this study aims to use space econometric models to explore the main economic behaviors that affect air pollution in Jiangsu Province, so as to promote the optimization of industrial models, strengthen the use of clean transportation, and increase environmental friendliness.

Many studies have investigated the factors that influence air pollution around the world. Most studies have shown that economic growth has significantly affected air pollution. Grossman and Krueger first introduced the environmental Kuznets curve (EKC) and numerous investigations have explored the relationship between economic growth and atmospheric pollution based on this theory [5]. The earliest research focused on the emissions of traditional pollutants such as CO_2, SO_2, and industrial waste gas [6,7], but the increased availability of data has changed the main attention to more representative pollutant indicators, such as $PM_{2.5}$ and PM_{10} [8,9]. In addition, other air quality indexes have been used in studies [10]. The logarithmic mean Divisia index (LMDI) model treats the economic scale as the most important factor that affects the emission of atmospheric pollutants [11]. Thus, four important air pollutants comprising suspended particulate matter (SPM), SO_2, NO_X, and CO have inverted U-shaped relationships with the gross domestic product (GDP) per capita [12]. Traditional measurement methods have also detected different relationships between atmospheric pollution and economic growth, such as U-shaped and N-shaped relationships [13,14]. The availability of spatial measurement methods has allowed researchers to question the rationality of the environmental Kuznets curve. In particular, it was shown that an inverted U-shaped relationship does not exist between ash pollution and GDP [15]. In China, air pollution also has obvious spatial spillover effects and high-emission group agglomeration characteristics [16,17].

Studies based on data regarding the industrial structure and urbanization in China demonstrated a positive impact of the industrial structure on smog, where the impact of urbanization on smog was greater when the industrial structure was more unreasonable [18]. A previous analysis of the relationships between the industrial structures and $PM_{2.5}$ levels in 29 provinces and cities in China showed that the impacts were greatest in the western region, followed by the central and eastern regions [19]; although other studies reached the opposite conclusion. It is considered that the level of industrialization is still not high in China and that industry will continue to dominate in the future even if industrial upgrading is not sufficient to improve the air quality [20,21]. Analyses of the impact of foreign direct investment (FDI) suggest that the introduction of FDI also leads to the transfer of severe polluting enterprises to China, thereby increasing air pollution [22,23]. In addition, many studies of the causes of atmospheric pollution indicate that environmental regulations, industrial structures, and energy structures all have significant effects on pollution with smog. The spatial measurement method has often been used to investigate the impacts of foreign trade, energy, and transportation on air pollution in China, but particularly industrial smoke and dust, and the results indicated positive effects [24]. A study based on the application of the STIRPAT model demonstrated that urbanization and environmental regulation had significant effects on air pollution in the eastern region of China [25]. In addition, it was shown that coal consumption and the proportion of secondary industry were significant factors that affected air pollution in all cities in the north, south, east, and west of China, and car ownership also had a significant impact on southern and eastern cities [26].

Thus, many studies investigated the factors that might affect atmospheric pollution, but they have various limitations. First, most of these studies only analyzed a single pollutant index, and thus failed to fully represent the overall pollution in various regions of China. Therefore, it is necessary to consider a variety of pollutants in research studies. Second, previous studies focused on a few specific areas and they did not analyze the air pollution problems in the entire region. However, there are obvious differences in air pollution within regions with large economies such as Jiangsu Province, and thus, research is necessary at the sub-regional level. Finally, most previous studies used traditional measurement methods and failed to comprehensively consider all of the potentially important factors related to air pollution and failed to use spatial measurement methods. In the present study, the effects of various factors on air pollution were analyzed in 13 cities in Jiangsu Province from 2000 to 2016 using the spatial Dubin model (SDM). Suggestions are provided in order to improve the atmospheric environment and air quality based on the results obtained in this investigation.

2. Research Design

2.1. Research Method

Exploratory spatial data analysis (ESDA) is a spatial data analysis method with an identification function, which is mainly used to explore the non-random or spatial auto-correlations of spatial distributions with two analysis methods comprising global domain spatial correlation and local spatial correlation. In analyses of the spatial differences in regions using ESDA, it is necessary to test and estimate the spatial correlation statistics for global spatial correlation analysis and local spatial correlation analysis.

2.1.1. Space Weight Setting

Before conducting metric spatial correlation tests, it is necessary to determine the spatial proximity between cities, where a spatial weight matrix can represent the interdependences between the geographic attributes of different spatial areas. The spatial weight matrices employed in spatial measurement empirical research mainly comprise the adjacent weight matrix, distance weight matrix, economic distance weight matrix, and nested weight matrix. The proximity weight setting is based mainly on whether the spatial sections are adjacent, but due to the frequent economic interactions between cities and the convenient transportation conditions, the interactions between the cities far exceed the neighboring relationships and the individual prefecture-level cities are not adjacent. There is an "island" in the study region, so a spatial distance weight matrix was employed in the present study. The distance weight matrix was set according to the reciprocal of the geographical distance between the two regions. The spatial interactions were stronger when the distance between the regions was closer, so a higher weight was set. The weight was set as follows:

$$W_{ij} = \begin{cases} 1/d_{ij}{}^2 & i \neq j \\ 0 & i = j \end{cases}, \tag{1}$$

where d_{ij} is the distance between two cities, and the distance between two points was calculated based on the latitude and longitude coordinates.

2.1.2. Spatial Correlation Test

Global spatial auto-correlation analysis is used for measuring the degree of spatial differences and spatial correlations between regions, which are generally calculated with the global Moran's I index and global Geary's C index. In the present study, the global Moran's I index was employed to test the spatial correlations among urbanization levels in various cities in China. The formula for the global Moran's I index is as follows:

$$\text{Moran's I} = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \overline{X}\right)\left(X_i - \overline{X}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\sum_{i=1}^{n}\left(X - \overline{X}\right)^2}, \tag{2}$$

where n is the total number of regions in the study area; W is the spatial weight, if region i is adjacent to region j, $W_{ij} = 1$; otherwise, the weight is 0; X_i and X_j are attributes of region i and region j, respectively, and $\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$ is the average of the attributes.

The value of Moran's I index generally ranges between (−1, 1). A value greater than 0 indicates a positive correlation, whereas a value less than 0 indicates a negative correlation. Values close to 1 or −1 indicate similar levels of agglomeration. A value close to 0 indicates that the attributes are randomly distributed or a lack of spatial correlation.

Under the assumptions given above, the significance of the Z statistic is commonly used for Moran's I index. The Z statistic is determined as follows:

$$Z = \frac{I - E(I)}{\sqrt{V(I)}}, \tag{3}$$

where *E(I)* is the theoretical mean and *V(I)* is the theoretical standard deviation. In general, according to the normal distribution test value, when the Z value is greater than the critical value of the normal distribution function at the 0.05 (or 0.01) or 1.65 (or 1.96) significance levels, a variable has a significant positive correlation with the spatial distribution.

The global Moran's I cannot indicate the spatial agglomeration of local regions, but local spatial auto-correlation analysis can be conducted to further analyze whether the observations are similar or different in local regions. The Moran's I scatter plot derived by local correlation analysis represents the local spatial correlations of urbanization development. In Moran's I scatter plot, the horizontal axis corresponds to the urbanization level standard value Z for the central city, and the vertical axis corresponds to the spatial lag variable WZ. The scatter plot is divided into four quadrants, which correspond to the relationships between the four regions and their neighboring regions. The relationships between the four quadrants are as follows:

(1) First quadrant (high–high): indicates that a high-level area is surrounded by other high-level areas.
(2) Second quadrant (low–high): indicates that a high-level area surrounds a low-level area.
(3) Third quadrant (low–low): indicates that the area and its surroundings are both low-level areas.
(4) Fourth quadrant (high–low): indicates that one area is high, and the surrounding areas are low.

In particular, the first quadrant indicates that the urbanization level, government capacity, and neighboring cities of the central city are higher. The third quadrant indicates that both the central city and the neighboring cities are lower. The first quadrant and the third quadrant have a positive spatial auto-correlation relationship. The second quadrant indicates that the central city is lower, and the neighboring cities are higher. The fourth quadrant indicates that the central city is higher, and the central city is lower. The second quadrant and the fourth quadrant have a negative spatial auto-correlation.

2.2. Space Panel Model

A spatial panel model is a panel data space econometric model based on the common panel model, which combines the characteristics of spatial metrology with the advantages of the panel model by considering the spatial and temporal two-dimensional features of variables and information. The spatial panel models mainly comprise the spatial lag model (SLM), spatial autoregression (SAR) model, and spatial Dubin model (SDM).

2.2.1. Spatial Lag Model

The SLM assumes that the dependent variable has a spatial dependence. A regional dependent variable is affected by the independent variables in the region, but also by the independent variables in the adjacent region:

$$y_{it} = \rho \sum_{j=1}^{N} w_{ij} y_{it} + x_{it}\beta + \mu_i + \varepsilon_{it}, \tag{4}$$

where N is the number of regions, w_{ij} is an element in the spatial weight matrix, ρ is the spatial lag coefficient, β is the independent variable regression coefficient, μ_i is the spatial individual effect, which can be decomposed into a fixed effect and random effect, and ε_{it} is a random error term that follows an independent distribution.

2.2.2. Spatial Autoregression Model

The SAR model assumes that the error term has spatial dependence and it measures the effect of the error in the dependent variable in an adjacent region on the value observed in the focal region:

$$\begin{aligned} y_{it} &= x_{it}\beta + \mu_i + u_{it} \\ u_{it} &= \lambda \sum_{j=1}^{N} w_{ij} u_{it} + \varepsilon_{it} \end{aligned} \tag{5}$$

where λ is the spatial error coefficient, u_{it} is the spatial correlation error term, and the other parameters are the same as those in the SLM.

2.2.3. Spatial Dubin Model

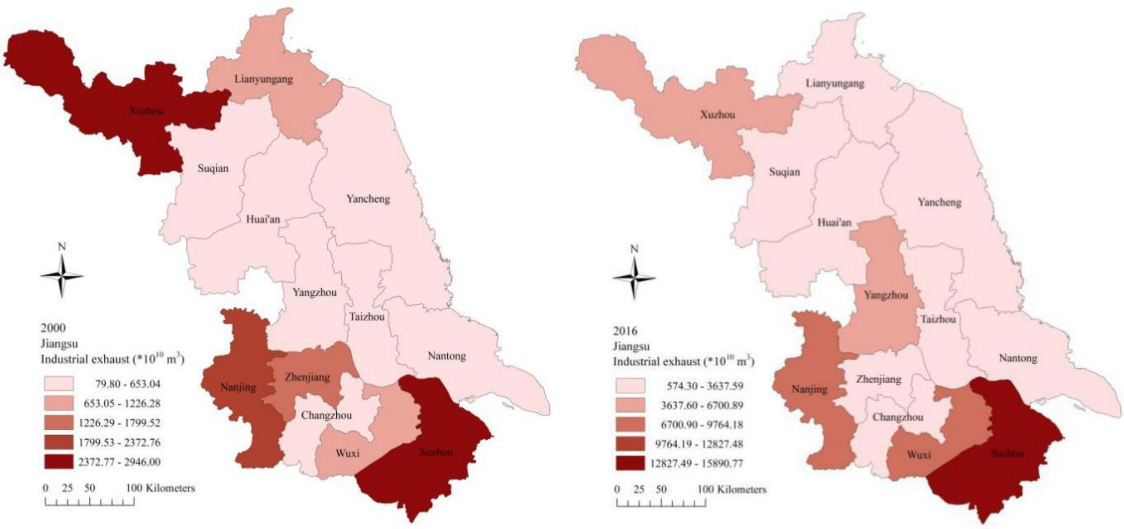
The SDM adds a spatial lag term for the independent variable based on the SLM and SAR. A regional dependent variable is affected by the dependent variable in the adjacent area, but also by the independent variable in the adjacent area:

$$y_{it} = \rho \sum_{j=1}^{N} w_{ij} y_{it} + x_{it}\beta + \gamma \sum_{j=1}^{N} w_{ij} x_{it} + \mu_i + \varepsilon_{it}, \tag{6}$$

where w_{ij} is the spatial lag of the independent variable in the adjacent region, γ is the spatial lag term coefficient for the independent variable, and the other parameters are the same as those in the SLM.

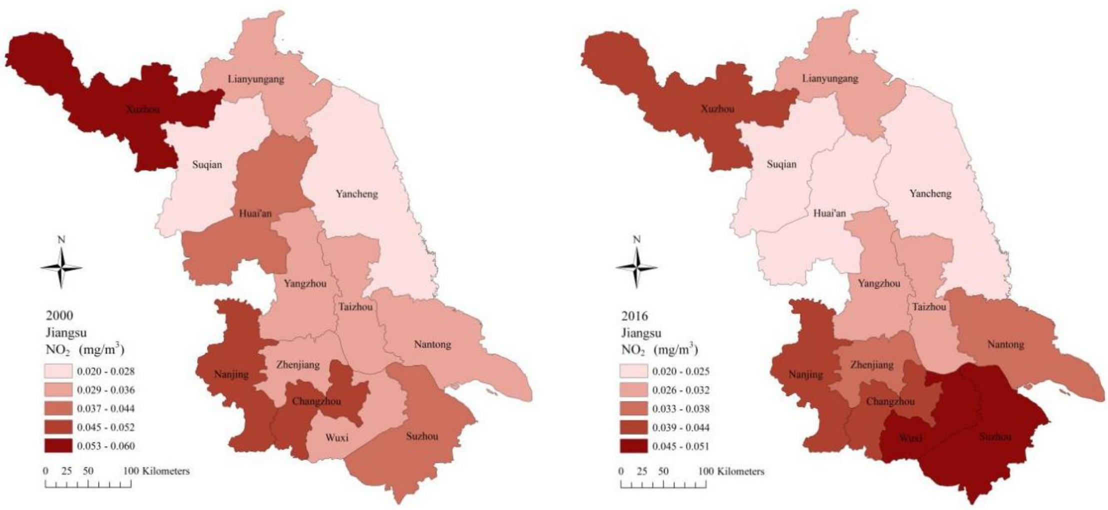
2.3. Variable Selection

Air pollutants (industrial waste gas emissions (IWGE) and nitrogen dioxide emissions (NO_2)): Many indicators can be used for measuring atmospheric pollutants, such as industrial waste gases, sulfur dioxide, industrial dust, nitrogen oxide emissions, and soot emissions [27]. However, industrial dust, soot emissions, and other indicators are not available for Jiangsu Province. Thus, IWGE and NO_2 data for Jiangsu Province during 2000–2016 were selected as the representative atmospheric pollutants comprising the dependent variables. The distribution of these two pollutants in 2000 and 2016 is shown in Figures 1 and 2. Jiangsu Province is a large manufacturing province with many industrial manufacturing enterprises, and thus, it produces a large amount of IWGE. Therefore, the IWGE value was selected as a representative indicator of atmospheric pollution. In addition, according to the Jiangsu Environmental Bulletin, the environmental air quality in 13 districts and cities did not reach the required standard in 2018. In particular, the NO_2 concentrations were significantly higher than the standard in Nanjing, Wuxi, Xuzhou, Changzhou, and Suzhou. NO_2 is a typical atmospheric pollutant and the main pollutant in economically-developed regions.



(a) 2000 **(b)** 2016

Figure 1. Industrial waste gas emissions distribution map of Jiangsu Province, China in (**a**) 2000 and (**b**) 2016.



(a) 2000 **(b)** 2016

Figure 2. Nitrogen dioxide (NO_2) emissions distribution map of Jiangsu Province, China in (**a**) 2000 and (**b**) 2016.

Population size (P): In general, larger populations consume more energy and the pollutant emissions are greater from industry. Short-term population agglomeration significantly increases the levels of atmospheric pollutants to reduce the air quality. Jiangsu is a large province with a growing population, a population agglomeration effect, and a severe pollution problem. Therefore, the population of each city was selected as an indicator to examine the relationship between population size and air pollution.

Economic growth level (per capita GDP, PGDP): The depletion of energy resources caused by human industrial production and living activities, and the problem of global warming have become serious issues that now affect society due to economic globalization. Economic development requires the consumption of large amounts of resources and energy, thereby causing severe harm to the atmosphere. Therefore, studying the relationships between economic growth levels and air pollution can help to find a balance between economic development and optimizing the atmospheric environment in order to minimize the harmful effects of economic growth on the atmosphere. In general, previous investigations employed PGDP as an indicator of economic growth [28], so real PGDP data for each city were used in this study.

Industrial structure (T_3): The added value of tertiary industry relative to the proportion of regional GDP was used to measure the industrial structure of each city. Tertiary industry is considered an industry with high economic returns characterized by environmental protection and low pollution. Enhancing the proportion of tertiary industry is the developmental aim in Jiangsu and essential for adopting a low-carbon sustainable development path. A higher output value for tertiary industry in a region indicates the presence of fewer highly-polluting enterprises and a low level of environmental pollution.

Level of rural modernization (E): Rural electricity consumption was used as an indicator to represent the level of rural modernization. In general, it is considered that the destruction of the atmospheric environment is less extensive in rural areas than urban areas, and thus the impact of rural areas on air pollution is negligible. In reality, the development of rural areas lags behind that of urban areas. Most of the industries in cities are energy-intensive and inefficient, and urban development is still in the industrial structure optimization stage, but the transfer of high energy-consuming industries to rural areas is accelerating. Therefore, it is particularly important to examine the degree of modernization in the rural areas of Jiangsu Province. High electricity consumption in rural areas indicates that rural enterprises consume more energy and produce higher amounts of air pollution.

Personal income (PI): According to the Kuznets curve, the relationship between environmental quality and economic growth is a U-shaped curve. As the per capita income increases during the initial stage of economic development, the environmental pollution and environmental pressure levels increase from low to high. After a critical point or turning point, the environmental pollution and pressure levels change from high to low as the per capita income increases further, and the environment is improved and restored. Therefore, the relationship between PI and air pollution in Jiangsu Province was investigated by using the incomes of urban residents in 13 cities.

Foreign direct investment (FDI): The impact of FDI on the quality of the environment is considered mainly based on the "polluting halo theory" and "pollution sanctuary" hypothesis [29]. Studies have suggested that a large amount of FDI can exacerbate atmospheric pollutant emissions. However, the introduction of foreign capital can lead to technology transfer and spillover and improves the technical level of the host country to reduce the use of resources and improve energy efficiency, thereby decreasing atmospheric pollutant emissions [30,31]. Jiangsu Province has high levels of FDI. Thus, analyzing the impacts of foreign investment levels on air pollution can provide theoretical guidance regarding future approaches to foreign investment. Therefore, the actual amount of FDI in each city was used as an indicator.

High-speed rail (G): Few studies have investigated the influence of high-speed rail on the atmospheric environment, but one suggested that high-speed rail suppresses air pollution [32]. High-speed rail can directly and indirectly improve the atmospheric environment by changing the travel mode and upgrading the industrial structure. Jiangsu Province is a developed transportation province and high-speed rail is in a rapid development stage since the introduction of the high-speed rail system in 2010. At the end of 2018, the total mileage of high-speed rail reached 30,000 km in this province. Therefore, in this study, a dummy variable was used where the presence of high-speed rail was assigned a value of 1 or 0 in order to examine the relationship between introducing high-speed rail and air pollution.

Urbanization level (U): No unified measures are available for quantifying the level of urbanization. The two main methods comprise the urbanization rate of the population as the proportion of the urban population relative to that of the total population, and the urbanization employment rate (i.e., the non-agricultural population calculated as the proportion relative to the total employed population). Most previous studies used the ratio of the urban population relative to the total population [25], so the population urbanization rate was also used in the present study.

Considering data collection limitations, the period considered in this study ranged from 2000 to 2016. Relevant data for the nine variables described above were derived from the 2001–2017 Jiangsu Statistical Yearbook, China Statistical Yearbook, and Jiangsu Statistics Bulletin. In addition, the data were converted into natural logarithms in order to avoid data volatility and possible heteroscedasticity. Table 1 shows the basic descriptive statistics for the above variables.

Table 1. Basic descriptive statistics for the variables.

Variable Type	Symbol	Unit	N	Avg	S	Min	Max
Explained variables	IWGE	Cubic meter	221	2432.38	2844.92	79.8	15,890
	NO_2	MG/m^3	221	0.038	0.012	0.015	0.08
Explanatory variables	P	10,000 people	221	588.774	188.912	289.3	1064.74
	PGDP	yuan	221	45,201.16	34380	3993	145,556
	T_3	%	221	39.15	5.962	26.8	58.39
	E	10,000 kw/h	221	9,224,497.6	1,340,216.6	26,872	7,500,000
	PI	yuan	221	19,403.62	11,226.79	4617	54,341
	FDI	Billion yuan	221	0.044	0.03	0.004	0.201
	G	Virtual variable	221	0.163	0.37	0	1
	U	%	221	0.532	0.164	0.137	0.98

Note: N—sample size, Avg—average, S—standard deviation, Min—minimum value, Max—maximum value, IWGE—industrial waste gas emissions, NO_2—nitrogen dioxide, P—population size, PGDP—per capita gross domestic product, T_3—the added value of tertiary industry, E—electricity, PI—personal income, FDI—foreign direct investment, G—high-speed rail, U—urbanization.

3. Results and Discussion

3.1. Spatial Correlation Analysis

Spatial measurement tools were used to analyze the factors that might influence air pollution. In order to confirm the validity of the spatial measurement tools, the spatial correlations with air pollution were tested using the global Moran's I index before the actual analyses. The test results are shown in Table 2, and demonstrate that the global Moran's I values ranged between −1 and 1. IWGE had a negative spatial correlation (i.e., areas with severe air pollution were adjacent to areas with less severe air pollution), and NO_2 had a positive spatial correlation (i.e., the areas with severe air pollution were adjacent).

Table 2. Moran's I index for atmospheric pollutants.

Year	IWGE		NO_2	
	Moran's I	Z Value	Moran's I	Z Value
2000	−0.219 **	−2.387	−0.007 ***	3.459
2001	−0.149 **	−2.64	−0.037 **	2.267
2002	−0.149 ***	−3.382	−0.043 ***	3.240
2003	−0.063 **	−2.116	−0.013 ***	3.400
2004	−0.254 ***	−2.981	0.009 ***	3.522
2005	−0.236 ***	−2.892	0.041 ***	3.702
2006	−0.161 ***	−3.421	0.039 ***	2.690
2007	−0.185 ***	−3.164	0.129 ***	3.188
2009	−0.223 ***	−3.376	0.186 **	2.487
2010	−0.179 **	−2.338	0.202 **	2.791
2011	−0.277 ***	−3.073	0.105	1.058
2012	−0.244 ***	−3.042	0.215 ***	2.757
2013	−0.245 ***	−3.908	0.196 ***	2.977
2014	−0.101 **	−2.399	0.137 **	2.263
2015	−0.189 ***	−3.097	0.262 **	2.567
2016	−0.027 ***	−3.327	0.309 **	2.264

Note: ***, **, and * indicate the level of significance of 1%, 5%, and 10%, respectively; IWGE—industrial waste gas emissions, NO_2—nitrogen dioxide.

3.2. Empirical Results

3.2.1. Analysis of Spatial Measurement Results

Three different models were used in order to compare the effects of various factors on industrial exhaust emissions and NO_2 emissions; the empirical results are shown in Tables 3 and 4. According to the Wald test and likelihood ratio test, the null hypothesis was not true, and thus, SAR model and SLM were rejected. Therefore, the SDM was used to analyze the effects of various factors on air pollution. In addition, according to the Hausman test results, the *p*-value was less than 0.01 for spatial measurement with IWGE as the explanatory variable, so the random effect model was rejected, and the fixed effect model was accepted. The *p*-value was greater than 0.01 for spatial measurement with NO_2 as the explanatory variable, so the random effect model was selected. Therefore, the SDM fixed effect model with IWGE and the SDM random effect model with NO_2 were employed in this study. In particular, the difference between random effects and fixed effects is that individual effects, which are the equations of individuals, have the same slope but different intercept terms, and exist in different forms. The intercept term in random effects is not related to all explanatory variables, while that in fixed effect is related to an explanatory variable. The results obtained with IWGE were in line with expectations, and the results with NO_2 in Table 4 were also consistent with those using IWGE. Therefore, only the results obtained using the SDM are presented in Table 3.

Table 3 shows the effects of various factors on industrial exhaust emissions. The regression coefficients were positive for population size and PGDP, and both passed the 1% significance level, thereby indicating that they had positive effects on the explanatory variables. A faster economic growth rate is associated with a larger population size and greater IWGE, thereby resulting in more severe air pollution. Jiangsu Province is still at a stage where air pollution is positively correlated with economic growth, mainly because its economic growth is driven by the development of secondary industry, and the increased industrial output leads to high industrial emissions. In addition, increased regional economic growth accelerates population agglomeration and exacerbates the pressure on the atmospheric environment. The correlation between the industrial structure and industrial exhaust emissions was not significantly negative, which indicates that optimizing the industrial structure by increasing the output value from tertiary industry will inhibit IWGE to some extent. Optimizing the industrial structure will decrease the proportion of secondary industry but increase the proportion of tertiary industry, which mainly comprises service industries with low IWGE outputs, thereby improving the atmospheric environment. The economic development in Jiangsu Province is at a high level for China and an economy of scale has been formed, so the economic structure is gradually improving. Therefore, at present, the government should continue to increase the proportion of tertiary industry and increase its output value in order to maintain the same economic aggregation and ease environmental pressure. Increasing rural electricity consumption and PI will significantly increase IWGE because coal-fired power generation dominates in Jiangsu Province, so increasing the consumption of electricity will utilize more coal and exacerbate industrial emissions. Increasing PI will enhance the demand for consumer products and increase industrial emissions to intensify the generation of air pollution. FDI was negatively correlated with industrial emissions and the coefficient passed the 5% significance level, thereby demonstrating that FDI can reduce industrial emissions. This is because Jiangsu Province has a developed economy, attracts good foreign investment, and has gradually lost its labor advantage. The manufacturing industry is shifting from labor-intensive industries and government policies are more focused on the environment, so increasing FDI will reduce air pollution. Similarly, an increase in the urbanization level can also decrease the level of pollution to improve the atmospheric environment. The development of urbanization is higher in Jiangsu Province than other provinces and has passed the U-shaped turning point. The degree of urbanization development at this stage has a negative impact on air pollution. The introduction of the high-speed rail system had a significantly positive effect at the 1% level, thereby indicating that high-speed rail increased air pollution, as expected. This is mainly because Jiangsu Province has many high-speed rail lines and the construction and maintenance of high-speed rail systems require industrial products, thereby increasing industrial exhaust emissions and severely polluting the atmospheric environment.

Table 3. Effects of various factors on IWGE.

Variables	SAR		SDM		SLM	
	FE	RE	FE	RE	FE	RE
P	0.317 *** (0.108)	0.278 *** (0.064)	0.715 *** (0.142)	−1.497 *** (0.245)	0.351 (0.262)	0.323 ** (0.142)
PGDP	−0.018 (0.015)	−0.008 (0.014)	0.094 *** (0.028)	−0.037 * (0.020)	−0.028 (0.022)	−0.018 (0.016)
T_3	0.063 ** (0.024)	0.072 *** (0.024)	−0.046 (0.032)	0.077 * (0.042)	0.067 * (0.036)	0.082 ** (0.033)
E	0.001 *** (0.000)	0.001 *** (0.000)	0.001 *** (0.000)	0.001 *** (0.000)	0.001 *** (0.000)	0.001 *** (0.000)
PI	0.108 *** (0.038)	0.069 * (0.036)	0.100 * (0.056)	−0.197 *** (0.071)	0.085 (0.065)	0.043 (0.043)
FDI	−0.489 * (0.263)	−0.392 (0.251)	−0.531 ** (0.255)	0.480 (0.452)	−0.558 (0.385)	−0.451 (0.312)
G	0.127 *** (0.023)	0.128 *** (0.023)	0.947 *** (0.027)	0.612 (0.045)	0.130 ** (0.057)	0.131 ** (0.055)
U	−0.232 ** (0.092)	−0.153 * (0.092)	−0.321 *** (0.086)	0.238 (0.167)	−0.227 (0.185)	−0.145 (0.142)
C	—	−0.106 (0.133)	—	−0.101 (0.217)	—	−0.092 (0.148)
Wald test SAR	—	—	122.420 *** (0.000)	122.420 *** (0.000)	—	—
LR test SAR	—	—	79.710 *** (0.000)	79.710 *** (0.000)	—	—
Wald test SLM	—	—	170.260 *** (0.000)	170.260 *** (0.000)	—	—
LR test SLM	—	—	80.520 *** (0.000)	80.520 *** (0.000)	—	—
Hausman(*p*)	—	—	32.910 (0.000)	32.910 (0.000)	—	—

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; standard deviations are indicated in parentheses; SAR—spatial autoregression model, SDM—spatial Dubin model, SLM—spatial lag model, FE—fixed effects, RE—random effects, C—constant, *p*—*p*-value.

Table 4. Effects of various factors on NO_2.

Variables	SAR		SDM		SLM	
	FE	RE	FE	RE	FE	RE
P	0.010 (0.010)	0.012 * (0.006)	0.005 (0.014)	0.009 (0.024)	0.011 (0.018)	0.012 (0.010)
PGDP	2.52×10^{-7} * (1.36×10^{-7})	2.91×10^{-7} ** (1.31×10^{-7})	1.01×10^{-7} (1.98×10^{-7})	6.32×10^{-7} ** (2.78×10^{-7})	2.55×10^{-7} (2.62×10^{-7})	3.01×10^{-7} (2.36×10^{-7})
T_3	-1.32×10^{-5} (0.000)	8.49×10^{-7} (0.000)	-1.42×10^{-6} (0.000)	-1.12×10^{-5} (0.000)	-1.64×10^{-5} (0.000)	-5.05×10^{-6} (0.000)
E	1.17×10^{-9} (1.00×10^{-9})	1.18×10^{-9} (9.62×10^{-9})	-1.09×10^{-9} (1.62×10^{-9})	3.76×10^{-9} (2.93×10^{-9})	1.18×10^{-9} (1.36×10^{-9})	1.22×10^{-9} (1.52×10^{-9})
PI	-4.61×10^{-7} (3.50×10^{-7})	-6.60×10^{-7} ** (3.34×10^{-7})	-4.64×10^{-7} (5.51×10^{-7})	-3.83×10^{-7} (7.05×10^{-7})	-4.64×10^{-7} (5.82×10^{-7})	-6.70×10^{-7} (5.35×10^{-7})
FDI	−0.052 ** (0.025)	−0.050 ** (0.024)	−0.049 * (0.025)	−0.052 (0.045)	−0.052 (0.041)	−0.050 (0.037)
G	−0.007 *** (0.002)	−0.007 *** (0.002)	−0.010 *** (0.003)	0.004 (0.004)	−0.008 * (0.004)	−0.001 * (0.017)
U	−0.004 (0.009)	−0.004 (0.009)	−0.005 (0.008)	−0.033 ** (0.004)	−0.004 (0.018)	−0.050 (0.037)
C	—	−0.002 * (0.001)	—	−0.001 (0.002)	—	−0.002 (0.002)
Wald test SAR	—	—	122.420 *** (0.000)	122.420 *** (0.000)	—	—
LR test SAR	—	—	79.710 *** (0.000)	79.710 *** (0.000)	—	—
Wald test SLM	—	—	170.260 *** (0.000)	170.260 *** (0.000)	—	—
LR test SLM	—	—	80.520 *** (0.000)	80.520 *** (0.000)	—	—
Hausman (*p*)	—	—	6.850 (0.445)	6.850 (0.445)	—	—

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; standard deviations are indicated in parentheses; SAR—spatial autoregression model, SDM—spatial dubin model, SLM—spatial lag model, FE—fixed effects, RE—random effects, C—constant, *p*—*p*-value.

3.2.2. Analysis of Sub-Regional SDM Results

Spatial effects can be classified as direct and indirect effects. According to the different sources of spillover effects, the coefficient estimates for each explanatory variable can be further divided into direct and indirect effects. Direct effects indicate the influence of the explanatory variable on air pollution in a region, whereas indirect effects indicate the influence of the explanatory variable on air pollution in the neighboring region and measure for counteracting atmospheric pollution in the region. In order to understand regional differences, Jiangsu Province was divided into three regions comprising southern Jiangsu, central Jiangsu, and northern Jiangsu. The relationships were analyzed between various factors and air pollution in different regions based on the direct effect and indirect effect levels using the SDM; the results are shown in Tables 5 and 6. The results in Table 6 are more significant and consistent with our expectations; thus, the results in Table 6 are the main focus in the following sections.

Table 5. SDM results obtained based on IWGE as the explanatory variable.

Variables	South Jiangsu		Central Jiangsu		North Jiangsu	
	DE	IE	DE	IE	DE	IE
P	0.402	0.071	0.061	0.098	−0.455	−0.127
	(0.031)	(0.378)	(0.633)	(0.101)	(0.437)	(0.652)
PGDP	6.55×10^{-8}	4.86×10^{-7}	-3.08×10^{-6} **	1.43×10^{-6}	-2.26×10^{-6} ***	3.00×10^{-6} ***
	(8.05×10^{-8})	(9.60×10^{-7})	(1.26×10^{-6})	(1.06×10^{-6})	(6.38×10^{-7})	(7.38×10^{-7})
T_3	0.002	0.004	−0.006	0.005	−0.017 ***	0.026 ***
	(0.010)	(0.011)	(0.009)	(0.010)	(0.004)	(0.008)
E	0.080 **	0.042	0.095	0.147	−0.028 *	0.103 ***
	(0.040)	(0.076)	(0.071)	(0.105)	(0.016)	(0.031)
PI	0.560 ***	−0.816 ***	0.201	−0.511 *	−0.107 **	−0.051
	(0.131)	(0.147)	(0.256)	(0.279)	(0.050)	(0.074)
FDI	−0.103	−0.755	0.130	−0.143	0.260	0.061
	(0.081)	(0.944)	(0.037)	(0.105)	(0.245)	(0.469)
G	0.101	0.101 **	—	—	0.043	0.132
	(0.000)	(0.051)			(0.027)	(0.084)
U	−0.012	0.623 **	0.231	−0.086	−0.260 **	0.158
	(0.189)	(0.263)	(0.194)	(0.223)	(0.245)	(0.217)

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; standard deviations are indicated in parentheses; DE—direct effects, IE—indirect effects.

Table 6. SDM results obtained based on NO_2 as the explanatory variable.

Variables	South Jiangsu		Central Jiangsu		North Jiangsu	
	DE	IE	DE	IE	DE	IE
P	0.006	0.035	−0.015	−0.353 ***	0.044	−0.102
	(0.030)	(0.036)	(0.058)	(0.094)	(0.041)	(0.062)
PGDP	0.174 **	0.150	−0.135	0.101	0.352 ***	0.223 ***
	(0.085)	(0.140)	(0.137)	(0.117)	(0.064)	(0.079)
T_3	−0.001	-3.23×10^{-6}	−0.002 ***	0.001	−0.001 ***	0.001
	(0.001)	(0.001)	(0.001)	(0.010)	(0.000)	(0.001)
E	0.002	0.002	0.024 ***	−0.019 *	0.004 ***	−0.004
	(0.004)	(0.007)	(0.007)	(0.010)	(0.001)	(0.003)
PI	-1.38×10^{-6}	8.70×10^{-7}	-1.23×10^{-6} ***	1.43×10^{-6} ***	1.29×10^{-6} ***	3.47×10^{-7}
	(1.13×10^{-6})	(1.29×10^{-6})	(2.42×10^{-6})	(2.77×10^{-6})	(4.63×10^{-7})	(7.02×10^{-7})
FDI	−0.066	−0.008	−0.057 *	−0.313 ***	−0.101 ***	−0.105 **
	(0.067)	(0.089)	(0.033)	(0.100)	(0.023)	(0.046)
G	0.003	0.003	—	—	0.001	0.005
	(0.000)	(0.004)			(0.003)	(0.008)
U	−0.033 *	0.023	0.023	0.070 ***	0.025 **	0.022
	(0.018)	(0.026)	(0.020)	(0.021)	(0.010)	(0.020)

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; standard deviations are indicated in parentheses; DE—direct effects, IE—indirect effects.

Table 6 shows that the indirect effect sizes of economic growth in southern Jiangsu, central Jiangsu, and northern Jiangsu were 0.15, 0.101, and 0.223, respectively. Thus, the economic growth levels in the neighboring regions increased by 1%, and the air pollution levels in southern Jiangsu, central Jiangsu, and northern Jiangsu increased by 0.15%, 0.101%, and 0.223%, respectively. Therefore, economic growth had spatial spillover effects on southern Jiangsu, northern Jiangsu, and central Jiangsu; the spillover effects were largest in northern Jiangsu and smallest in southern Jiangsu. The economic growth rate in northern Jiangsu was much larger than those in the other regions, and due to the Province's policy of promoting economic development, the rapid growth in northern Jiangsu region promoted the economic development of the neighboring urban areas, thereby increasing the atmospheric pollution in the neighboring regions.

The direct effects of the industrial structure on southern and northern Jiangsu were negative, and the 1% significance level indicates that the optimization of the industrial structure decreased pollution in large areas of central and northern Jiangsu. However, regional industrial upgrading in these regions has led to shifts to high-energy and high-pollution industries, thereby exacerbating pollution in the surrounding areas and increasing the pressure on the environment. The industrial upgrading of southern Jiangsu optimized the industrial structure in the surrounding areas and improved the atmospheric environment. The direct and indirect effects of the central area were significant on rural electricity consumption. Thus, increasing the rural electricity consumption and the level of modernization led to decreased air pollution in the surrounding areas because increasing the electricity consumption in a certain area affected the atmospheric environment and the electricity consumption in the surrounding areas. The direct and indirect effects of FDI on each area were negative. Thus, FDI improved the air quality in the region and the neighboring areas. This is mainly because Jiangsu's economy is developing rapidly and the quality of FDI introduced is relatively high. The government has set a high threshold for foreign capital flow, so foreign-funded enterprises must be highly efficient, thereby reducing the level of air pollution. The direct and indirect effects of high-speed rail were positive in southern and northern Jiangsu. Thus, introducing the high-speed rail system increased the level of air pollution in the region, but also in the surrounding area. The effect of the high-speed railway system was much higher in southern Jiangsu than northern Jiangsu, and the direct effect was greater in southern Jiangsu than northern Jiangsu. Increasing the urbanization level will reduce the air pollution in southern Jiangsu but increase it in central and northern Jiangsu because the economic development is rapid in southern Jiangsu and the level of urbanization is greater. Due to the scale and speed of urbanization at the expense of the environment in the central and north regions, the environmental quality has degraded during the urbanization process in southern Jiangsu. Clearly, the level of urbanization development and the air quality require greater consideration in southern Jiangsu. However, according to the indirect effects, increased urbanization in the region has degraded the atmospheric environment in the neighboring areas because increased urbanization has increased the demand for consumer products in the region. Thus, the transactions between regions during this process have led to increased emissions of atmospheric pollutants in adjacent areas.

In general, the levels of economic growth, FDI, and urbanization were the main factors that affected air pollution in the different regions. The direct effects were generally greater than the indirect effects, thereby indicating that the explanatory variables had greater impacts on atmospheric pollution in the focal region than the adjacent regions. The direct effects were more significant in northern Jiangsu and central Jiangsu, and the indirect effects were more significant in central Jiangsu.

3.3. Robustness Test

The robustness test examines the robustness of the evaluation methods and the ability to interpret the indicators; that is, whether certain evaluation methods and indicators still maintain a relatively consistent and stable interpretation of the evaluation results when certain parameters are changed. In order to check whether the results are robust, the methods for performing the robustness test include using other measurement methods such as ordinary least square (OLS) or replacing some variables. Therefore, this paper uses both methods at the same time; the robustness test results are shown in Table 7.

Table 7. Robustness test results.

Var	$PM_{2.5}$	IWGE							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
P	0.305 ** (0.001)	0.353 *** (0.083)	0.309 *** (0.084)	0.306 *** (0.100)	0.274 ** (0.110)	0.121 ** (0.122)	0.098 * (0.114)	0.159 * (0.091)	0.148 ** (0.096)
PGDP	3.61×10^{-6} ** (4.72×10^{-6})	—	0.008 ** (0.001)	0.003 * (0.003)	0.003 * (0.003)	0.012 *** (0.004)	0.005 ** (0.004)	0.004 * (0.004)	0.006 ** (0.004)
T_3	0.020 (0.009)	—	—	−0.004 ** (0.003)	−0.002 * (0.003)	−0.002 * (0.003)	−0.001 * (0.003)	−0.002 * (0.003)	−0.001 * (0.003)
E	4.98×10^{-8} ** (8.40×10^{-8})	—	—	—	0.033 * (0.001)	0.031 ** (0.002)	0.014 ** (0.001)	0.013 ** (0.001)	0.003 * (0.001)
PI	1.59×10^{-6} (0.000)	—	—	—	—	0.013 *** (0.005)	0.005 ** (0.001)	0.003 * (0.005)	0.004 * (0.004)
FDI	−0.720 ** (0.859)	—	—	—	—	—	−0.050 *** (0.001)	−0.043 ** (0.001)	−0.039 *** (0.001)
G	0.015 ** (0.082)	—	—	—	—	—	—	0.013 * (0.002)	0.011 * (0.004)
U	−0.190 * (0.300)	—	—	—	—	—	—	—	−0.006 * (0.003)
C	—	−0.803 ** (0.226)	−0.858 ** (0.228)	−0.911 (0.258)	0.021 (0.019)	−0.309 (0.316)	−0.251 (0.294)	−0.434 * (0.230)	−0.378 (0.244)

Note: ***, **, and * indicate significance levels of 1%, 5%, and 10%, respectively; standard deviations are indicated in parentheses; Var—variables, $PM_{2.5}$—particulate matter with a diameter less than or equal to 2.5 microns, IWGE—industrial waste gas.

From the perspective of variable, robustness testing can be performed by replacing core variables. China's coal-based energy consumption structure determines that industrial waste gas emissions are the main source of air pollution. In addition, $PM_{2.5}$ (particulate matter with a diameter less than or equal to 2.5 microns) can be converted from sulfur and nitrogen oxides in the waste gas, resulting in increased air pollution [33]. Therefore, $PM_{2.5}$ is used to measure air pollution and the robustness test on the spatial Dubin model regression results is tested in this paper. The results are shown in column (1) of Table 7. Using other measurement methods is also a common method for robustness testing. Given many variables involved in this article, there may be correlations between the variables. Therefore, using the OLS method can remove the unimportant variables and eliminate the problem of collinearity. The regression results are shown in columns (2)–(9) of Table 7.

From the above results, it can be seen that the regression results are all significant, and the sign of the regression coefficient is consistent with the benchmark regression. The regression results are more robust.

4. Conclusions

In this study, IWGE and NO_2 were selected as representative air pollutants, and data from 2000–2016 in Jiangsu were used to analyze the effects of eight related factors on air pollution with the SDM. The effects of each factor on air pollution as well as the direct and indirect effects of each factor were measured at the regional level. The main conclusions based on the results are as follows: (1) The population size, economic growth level, rural modernization level, PI, and high-speed rail were positively correlated with air pollution, whereas the industrial structure, FDI, and urbanization level were negatively correlated with air pollution. The effects of PI, FDI, high-speed rail, and urbanization were significant. (2) At the sub-regional level, the effects of economic growth level, FDI, and urbanization were significant, and spatial spillover effects were detected. The spatial spillover effects were most obvious in northern Jiangsu and central Jiangsu. The direct effects were greater in each region than the indirect effects.

In addition to its contribution to the literature, this study also has practical implications: First, the findings of this study confirm that irrational industrial structure exacerbates air pollution, therefore, the industrial structure should be adjusted to improve the mode of economic development. It is necessary to consider the environmental cost of economic development, as well as increase the proportion of the output value from the clean third industry and promote the use of clean energy and energy-saving technologies in industry. Investment should be increased in innovative enterprises and high-end service industries. In addition, stimulating enterprises and promoting the transformation from a resource-heavy economy to an innovation-driven development mode provide a suitable environment for innovation and development, and reduce the emissions of atmospheric pollutants [34]. Second, this study suggests that the spatial heterogeneity of Jiangsu Province determines the need for specific development policies in different regions. Thus, the southern part of Jiangsu should encourage innovation, accelerate structural transformation, promote a green economic development mode, and drive other regions to develop their own developmental advantages. The central and northern areas should strengthen the construction of infrastructure, accelerate the urbanization process, encourage the flow of funds and talents between cities, prevent the transfer of high energy-consuming industries within the province, establish local characteristics and advantageous industries, treat successful cities as models, and promote the transformation of other resource-based cities. Third, some other factors, such as FDI and railway construction, should be taken into consideration. FDI should be introduced in a reasonable manner. The government should actively guide the transfer of FDI to cleaner service industries and low-carbon environmental protection industries and increase the output value from tertiary industry. Strict reward and punishment systems should be implemented as well as a standardized management system for enterprises to enhance corporate environmental awareness. Further, railway construction should be conducted in a rational manner and green travel must be promoted. The future development of high-speed rail in Jiangsu must consider the atmospheric environment. In addition, green travel should be encouraged by providing financial subsidies to promote the development of new energy vehicles and the development of urban public transportation, as well as increasing public awareness of environmental protection and energy conservation.

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