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Spatio-Temporal Variation of Carbon Emission Intensity and Spatial Heterogeneity of Influencing Factors in the Yangtze River Delta

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Abstract: The Yangtze River Delta plays an important strategic role in China's economic development pattern, and its carbon emission intensity, which reflects the development of a low-carbon economy, has attracted much attention. From the perspective of the city-level, this study uses the coefficient of variation, spatial autocorrelation and the Multi-scale Geographically Weighted Regression (MGWR) model to study the spatio-temporal characteristics of carbon emission intensity in the Yangtze River Delta from 1997 to 2017 and the spatial heterogeneity of its influencing factors. The results indicated that: (1) the carbon emission intensity in the Yangtze River Delta increased first and then decreased during the sample period, and the number of low-carbon emission intensity zones decreased first and then increased. (2) Through the coefficient of variation analysis, it is known that the ratio of nugget value to base value is much less than 25%, indicating that the correlation between the cities in the Yangtze River Delta is becoming more and more obvious, the spatial difference is becoming smaller, and the integration level is growing higher and higher. (3) The carbon emission intensity of the Yangtze River Delta has a strong positive spatial correlation, and the carbon emission intensity of the Yangtze River Delta decreases from the north to the south. (4) The effect of population size on carbon emission intensity is bidirectional, but the inhibition effect is greater than the promotion effect, and the average regression coefficient is −0.0796; the average regression coefficient of economic development level is 0.3674, and the average regression coefficient of industrial structure is 0.1702, both of which have a positive impact on carbon emission intensity. The degree of urbanization has a bidirectional effect, and the regression coefficient ranges from −0.920 to 0.091, and the negative effect is quite strong. Additionally, each factor has spatial heterogeneity.

Keywords: carbon emission intensity; spatial heterogeneity; MGWR model; influencing factors; Yangtze River Delta

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1. Introduction

Climate warming is an important global environmental problem, and a large amount of carbon dioxide is regarded as an important factor causing global climate warming. Since industrialization, the global economy has developed rapidly, and more than 90% of human activities have caused a surge in the consumption of traditional fossil energy, such as oil and coal. As a result, the greenhouse gas emissions in the past 50 years have caused a continuous rise in global temperature, which has exerted a serious impact on the sustainable development of the natural and human living environment. Since the reform and opening up policy, China's economy has continued to grow, and the industrialization process has been promoted rapidly, thus driving the long-term high growth of traditional fossil energy consumption. As a consequence, China's carbon emission has become the focus of global attention. In response to the serious problem of global warming, the UN has set up the Intergovernmental Panel on Climate Change and held many international climate conferences to actively explore energy conservation and emission reduction measures, promote global cooperation consensus on green and low carbon development, and sign the Kyoto Protocol and the Paris Agreement on Climate Change. In order to realize the transformation of economic development mode to green, low carbon and high-quality development [1,2], China has put forward the goal of reducing carbon emission intensity by 60% to 65% compared with 2005 in 2030 and promised to achieve carbon neutrality in 2060.

In recent years, European countries have been major contributors to global carbon emissions reduction, while emissions in the Asia-Pacific region have grown rapidly, with a larger increase in China. As a world-class city cluster with intense vitality and comprehensive competitiveness, the Yangtze River Delta region should contribute to the co-governance of carbon emissions and global climate governance. Depending on a recent report by the World Resources Institute (WRI), China's total carbon dioxide emissions have tripled in the past 20 years, with most of the emissions concentrated in north and east China. Located in East China, the Yangtze River Delta is part of the three economic zones in China. With the rapid development of urbanization and industrialization, there is a great demand for fossil energy consumption, maintaining carbon emissions at a high level. Shouldering the tactical mission of exploring a new pattern of regional development, the Yangtze River Delta region is a national demonstration area for high-quality integrated development and an important region for realizing the goal of "dual-carbon" [3]. The Yangtze River Delta is a major intersection of the Belt and Road Initiative and the Yangtze River Economic Belt. However, the rapid development of the economy and urbanization stimulates the rapid growth of carbon emissions [4], increases the urban heat island effect [5], intensifies the trans-regional pollution of PM2.5, and causes the conflict between urban development and air quality [6]. If economic growth and environmental pollution in the Yangtze River Delta are developed [7] and green economies are developed, it is urgent to solve the problem of carbon emission. Therefore, it is of great practical significance to measure the spatio-temporal evolution law of municipal emission intensity in the Yangtze River Delta region and explore the internal driving mechanism of carbon emission intensity in different regions for the early realization of green, low carbon, and high-quality development in the Yangtze River Delta region and the sustainable development of regional economy and society, and to provide practical experience for China's dual carbon goal.

Carbon emission intensity (*CEI*) has become a measure of high-quality economic development and has significant spatial clustering and spatial correlation, so the decline in carbon emission intensity has caught the attention of many scholars [8]. China's carbon emission efficiency is characterized by low in the northwest and high in the southeast of the Hu Huanyong Line [9], and the carbon emission intensity of major strategic regions presents a spatial pattern of "low in the south and high in the north" on the whole [10]. The Yangtze River Delta is an area with concentrated energy consumption, complex transportation, and population size, and is also one of the regions with relatively concentrated carbon emissions [11]. In terms of the spatio-temporal characteristics of carbon emissions, more and more scholars have used the Theil coefficient [12], Lorentz curve and Gini coefficient [13], coefficient of variation, kernel density estimation [14], hot spot analysis [15], spatial autocorrelation [16], spatial Markov chain [17], and other methods to study the spatio-temporal heterogeneity of carbon emission intensity. It mainly includes regional differences, spatial agglomeration, and spatial correlation. In terms of the influencing factors of carbon emission intensity, Liu Fang [18] used the Logarithmic Di mean index decomposition method (LMDI) to study that economic output, industrial structure, energy intensity and energy structure are all related to carbon emission changes. Zhu Dongyuan [19] expanded and analyzed the driving factors affecting carbon emissions in the Yangtze River Economic Belt with the help of the STIRPAT model. Wei Yanting [20] used the spatio-temporal geographical weighted regression model (GTWR) to analyze the influencing factors of carbon emissions in the Chengdu–Chongqing urban agglomeration. Based on the MGWR model, Chen Siyu [21] proposed that compared with the traditional GWR model, the MGWR model takes spatial scale difference into account, making the model more reasonable.

This study explores the spatial-temporal variation, heterogeneity, and influencing factors of carbon emission intensity in the Yangtze River Delta at the city scale, which will provide essential references for carbon reduction and sustainable economic development in the Yangtze River Delta region. Data collection processes, data characteristics, and the data processing and analysis methods are presented in Section 2. In Sections 3.1–3.3, the spatio-temporal variation in carbon emission intensity and the spatial heterogeneity of influencing factors are analyzed and reviewed. In Section 4, the existing problems are examined, and conclusions are drawn.

2. Data Sources and Research Methods

2.1. Study Area

The Yangtze River Delta is situated in the middle and lower reaches of the Yangtze River plain in East China. It is the alluvial plain before the Yangtze River enters the sea and an important part of the plain. According to the Outline of the Plan for the Integrated Development of the Yangtze River Delta Region approved by China in 2019, the Yangtze River Delta region consists of three provinces and one city: Anhui, Jiangsu, Zhejiang, and Shanghai, covering 358,000 square kilometers (Figure 1). Most areas are below 10 m above altitude, and there are a few low hills 200~300 m above altitude. There are numerous rivers and lakes and dense water networks. The climate is subtropical monsoon climate. In recent years, with the continuous improvement in the level of efficiency, the continuous expansion of the population and the rapid development of industrialization in the Yangtze River Delta, the problem of carbon pollution has not been fundamentally solved. Therefore, studying the spatio-temporal variation characteristics of carbon emission intensity and the spatial heterogeneity of the influencing factors certainly has scientific significance for solving the problem.

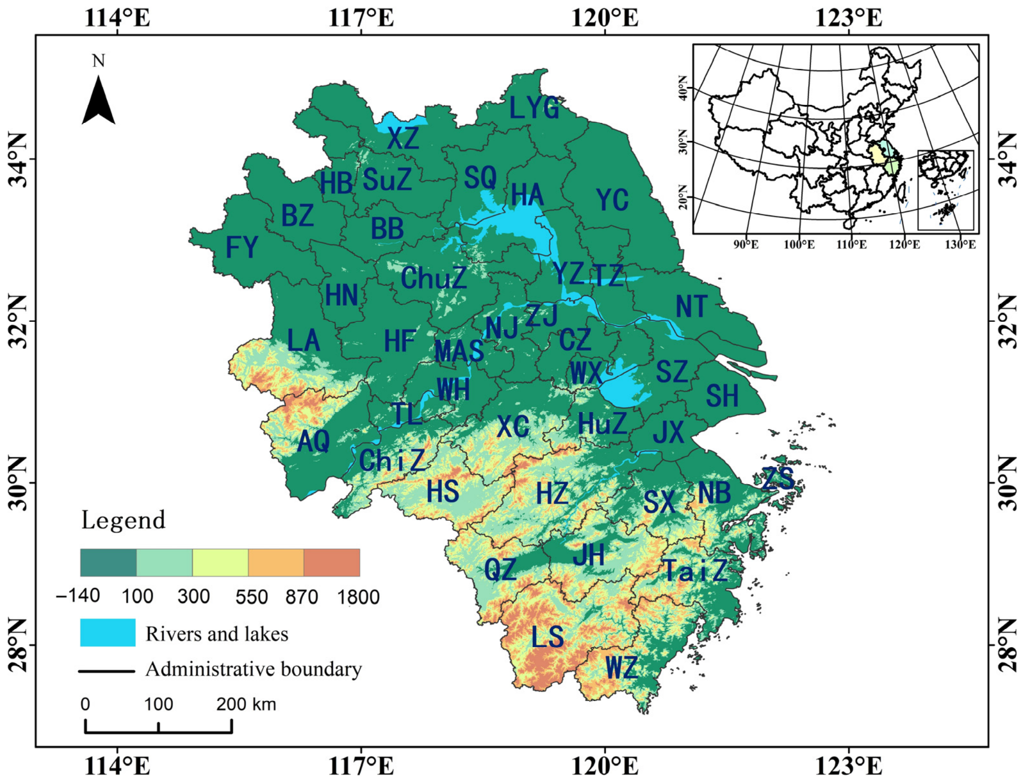

Figure 1. Administrative scope and geographical location of the Yangtze River Delta.

2.2. Data Sources

The data utilized in this paper include regional carbon emission data of the Yangtze River Delta from 1997 to 2017 and regional statistical data of the Yangtze River Delta from 1997 to 2017.

2.2.1. Carbon Emission Data

City-level carbon emission datasets from 2000 to 2017 were obtained from Carbon Emission Accounts and Datasets of China (CEADs) (http://www.ceads.net (accessed on 20 June 2022)). These datasets were obtained using the particle swarm optimized back propagation (PSO-BP) algorithm to invert two sets of nighttime light images as Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) and National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (NPP/VIIRS), provided by the National Physical Earth [17,22].

2.2.2. Statistical Data

In order to further explore the driving factors of temporal and spatial variation and heterogeneity of carbon emission intensity in the Yangtze River Delta, this paper selects the corresponding indicators from population, economy, and technology according to the Impact-Population-Affluence Technology (IPAT) theory proposed by Ehrlich [23]. In the selection of the population indicators, the total population at the end of the year, which is closely linked to carbon emissions, is selected as the population indicator. In terms of economy, we choose two indicators: per capita GDP and urbanization degree. In terms of technology, it mainly studies the industrial structure related to carbon emissions and chooses the proportion of the secondary industry in GDP. These impact indicators are all from the statistical yearbook of each province and city and the official website of the Bureau of Statistics.

2.2.3. Vector Data of Urban Administrative Districts in the Yangtze River Delta

The vector data of the Yangtze River Delta with a scale of 1:1,000,000 was taken from the National Catalogue Service For Geographic Information (https://www.webmap.cn/main.do?method=index (accessed on 25 June 2022)). The overall current situation of the dataset is 2019. The datum is from the National Geodetic Coordinate System 2000 and the National Datum 1985.

2.3. Methods

2.3.1. Calculation of Carbon Emission Intensity

Calculating a region's carbon emission intensity requires obtaining its carbon dioxide emissions and gross regional product. Taking this into account, the carbon dioxide emissions of all counties in the Yangtze River Delta region from 1997 to 2017 were estimated. This paper summarized and calculated the carbon emission data of all cities in the region.

Carbon emission intensity (*CEI*) refers to the carbon emissions generated by the growth of gross regional product per unit, and the carbon emission intensity reflects the ecological cost brought by economic production to a region [24]. The calculation formula for carbon emission intensity is as follows:

$$CEI = C/GDP \tag{1}$$

In Formula (1), C is carbon emissions in millions of tons; *CEI* is carbon emission intensity in t/ten thousand yuan *GDP*.

2.3.2. Coefficient of Variation

The coefficient of variation is a normalized measure of the degree of dispersion of the probability distribution, defined as the ratio of standard deviation to the mean. In the study of regional carbon emission intensity, the coefficient of variation can directly reflect the changing trend of carbon emission intensity. In this paper, the coefficient of variation is utilized to explore the variation trend and difference in the carbon emission intensities among cities in the Yangtze River Delta region. The formula for calculating the coefficient of variation is as follows:

$$C.V = \frac{\delta}{\alpha} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}}}{\overline{x}} \quad (2)$$

In Formula (2), δ represents the standard deviation and α represents the mean value.

2.3.3. Spatial Autocorrelation

In the global correlation analysis, the most commonly used variable is the global Moran's index, which represents the correlation degree between a region and its surrounding areas. The carbon emission intensity of each urban area is closely related, and the closer the urban area is, the closer the correlation is [25]. In this paper, the global Moran's Index is utilized to analyze the spatial characteristics of urban carbon emission intensity in the Yangtze River Delta. The formula for calculating global Moran's index is as follows:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}(X_i - \overline{X})(X_j - \overline{X})}{S^2} / \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij} \quad (3)$$

In Formula (3), n is the number of cities in the Yangtze River Delta studied; X_i and X_j respectively, studied city i and city j carbon intensity; $\overline{X}$ as the sample mean; W_{ij} weighting matrix for the space; $S^2 = \sum_{i=1}^{n}(X_i - \overline{X})^2 / n$; I is the global Moran index of carbon emission intensity, and the value interval is $[-1, 1]$ [26]. If the value is greater than 0, it indicates that the carbon emission intensity of the region has a positive correlation in space; that is, the city-level regions with higher or lower carbon emission intensity tend to cluster in space. If it approaches 0, it means that the distribution is random and there is no spatial correlation. If the value is lower than 0, it indicates that the carbon emission intensity of the region has a negative correlation in space and that there are differences in carbon emissions between adjacent municipal regions.

In order to further understand the local aggregation of carbon emission intensity in the Yangtze River Delta region, significant hot spots (high-value clustering), cold spots (low-value clustering), and spatial outliers can be identified through the local Moreland index. The global Moran index can be considered as the linear regression coefficient of spatial lag to carbon emission intensity. Through the LISA aggregation diagram of the local Moran's index, the cold and hot spots can be seen more intuitively from the map. The local Moran index calculation formula is as follows:

$$I_i = \frac{(X_i - \overline{X})}{\sum_{i=1}^{n}(X_i - \overline{X})^2} \sum_{j=1}^{n} W_{ij}(X_i - \overline{X}) \quad (4)$$

2.3.4. Multi-Scale Geographical Weighted Regression Model (MGWR)

The spatial scale is the basic category of geography and spatial integrated humanities and social sciences. Michael F Goodchild [27], a famous geographic information scientist, proposed that "scale is the most important thing topic in geographic information science". The multi-scale geographical weighted regression model (MGWR) is one of the cutting-edge methods to reveal the multi-scale causes and processes behind various human economic and social phenomena. In the classical GWR model, the optimal bandwidth of all independent variables is the same, that is, the average of the optimal bandwidth of all independent variables. By relaxing the assumption that the scale of the spatial process of all local coefficients is the same, a more powerful and explanatory model, MGWR, is obtained. The essential feature of MGWR is that the bandwidth of each independent variable is able to be different, and the heterogeneity scale of the differentiation between the coefficients is considered. The basic expression of the MGWR model is as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{j=1}^{n} \beta_j(u_i, v_i)x_{ij} + \varepsilon_i \quad (5)$$

In Formula (5), i = 1, 2, 3, . . . , n, (u_i, v_i) is the spatial coordinate of the i geographic position, and β_j is the bandwidth of the regression coefficient of the j explanatory variable.

3. Result

3.1. Temporal Variation of Carbon Emission Intensity in the Yangtze River Delta

As the largest economic zone in China, with the development of the industrial economy, the relationship between carbon emissions and the economy in the Yangtze River Delta is particularly important. As can be seen from Figure 2 (the top two GDP cities in each province are selected), although the carbon emission intensity of the selected cities fluctuates over time, it generally increases first and then decreases during the sample period. This shows that the Yangtze River Delta region has carried out industrial optimization of industrial development. In recent years, the Yangtze River Delta region has implemented the economic strategy of "green development" to strengthen environmental management. In terms of the overall trend, the carbon emission intensity of Hefei decreased the most, and the absolute value of the decrease reached 0.82 tons/10,000 yuan, indicating that the relevant measures on the carbon emissions of Hefei have achieved effective results. However, the carbon emission intensity of Suzhou increased rather than decreased, and the absolute value of the increase reached 3.64 tons/10,000 yuan. However, after reaching the peak, the carbon emission intensity gradually decreased, indicating that although the carbon emission intensity of Suzhou increased significantly during the sample period, it was also effectively controlled. Before 2002, only Hefei's carbon emission intensity was greater than the average of the entire Yangtze River Delta region, but after 2002, all of the provincial capitals were smaller than the average of the Yangtze River Delta region. This indicates that cities with higher GDP have lower carbon emission intensities and higher levels of low-carbon economic development.

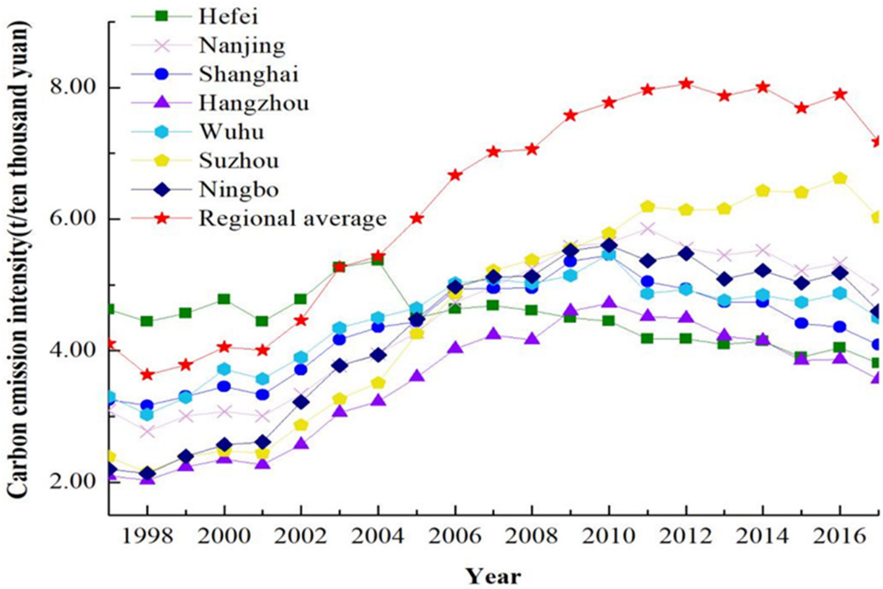

Figure 2. Temporal variation of carbon emission intensity of typical cities in the Yangtze Delta from 1997 to 2017.

As can be seen from Figure 3, the carbon emission intensity of the 42 cities in the Yangtze River Delta basically increased at first and then decreased over time. Huai'an City showed the greatest decrease from 5.17 tons/10,000 yuan to 0.81 tons/10,000 yuan, while Fuyang City showed the greatest increase in the absolute value of 10.57 tons/10,000 yuan.

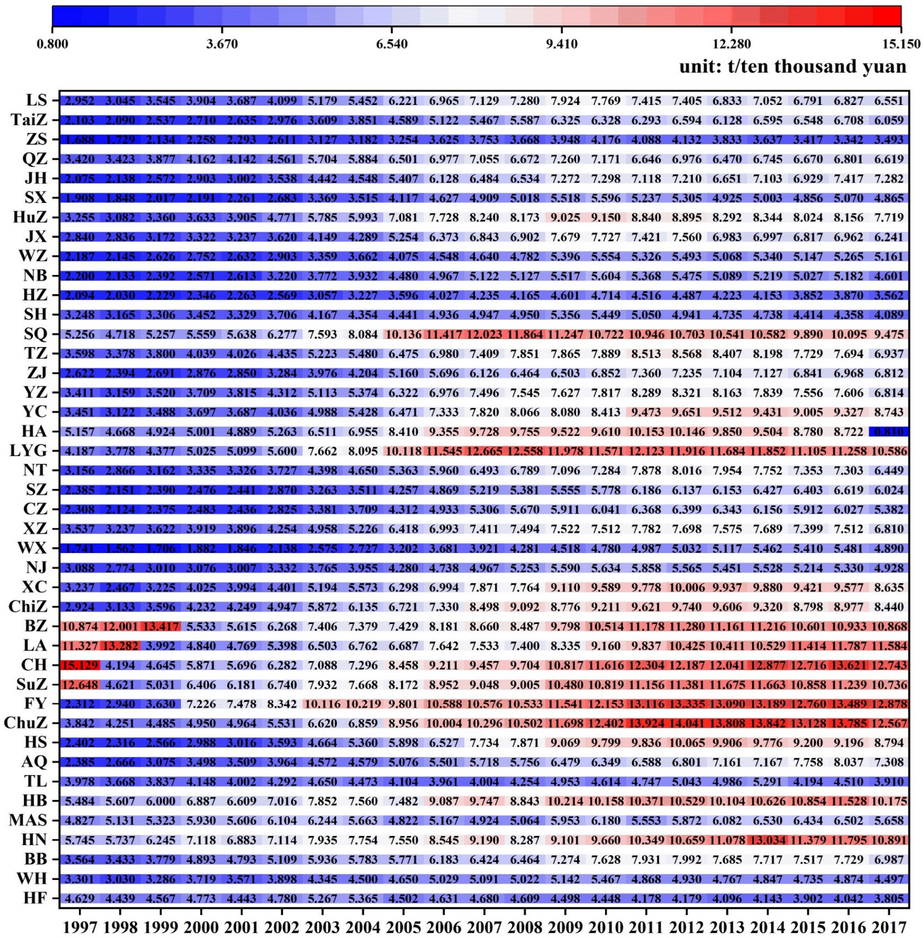

Figure 3. Temporal variation heat map of carbon emission intensity in cities of the Yangtze River Delta from 1997 to 2017.

3.2. Spatial Variation of Carbon Emission Intensity in the Yangtze River Delta

3.2.1. Spatial Variation of Carbon Emission Intensity

The natural break point method was used to divide the carbon emission intensity in the Yangtze River Delta into five levels (Figure 4). Figure 4 shows the classification levels of carbon emission intensity in the study area in 1997, 2005, 2010, and 2017. As can be seen from the figure, in 1997, the high carbon emission intensity zones were located in Chaohu City, Lu'an City, Bozhou City and Suzhou City, the medium carbon emission intensity zones were located in Huainan City, the second lowest carbon emission intensity zones were located in Hefei City, Lianyungang City, Suqian City, Huaibei City, Huai'an City, Tongling City and Ma'anshan City, and the other areas were in the low-carbon emission intensity zones. In 2005, the second highest carbon emission intensity zones were located in Chaohu City, Chuzhou City, Suqian City, Huai'an City, Fuyang City, Suzhou City and Lianyungang City, while the medium carbon emission intensity zones were located in Lu'an City, Bengbu City, Huainan City, Bozhou City, Huaibei City, Xuzhou City, Yancheng City, Yangzhou City, Taizhou City, Lishui City, Quzhou City, Huangshan City, Huzhou City, Xuancheng City, Chizhou City and 15 other cities. The low-carbon emission intensity zones were located in Hangzhou and Wuxi, while the other regions were in the second-lowest carbon emission intensity zones. In 2010, there were 21 cities in the second-lowest carbon emission intensity zones and medium carbon emission intensity zones. In 2017, the low-carbon emission intensity zones were located in Hefei, Huai'an and Hangzhou, and there were

25 cities in the second-lowest carbon emission intensity zones and the medium carbon emission intensity zones. The number of regions in the low-carbon emission intensity zones decreased first and then increased, indicating that the carbon emission intensity generally increased first and then decreased during the sample period. Moreover, the number of cities in the low-carbon emission intensity zones and the second-lowest carbon emission intensity zones in the south was more than that in the north. Therefore, inclusive regulation of carbon emission intensity in each city was the key to controlling the carbon emission intensity in the Yangtze River Delta. Therefore, the strategy of energy conservation and emission reduction in the Yangtze River Delta can achieve complementary emission reduction by promoting regional cooperation so as to reduce carbon emission intensity more effectively.

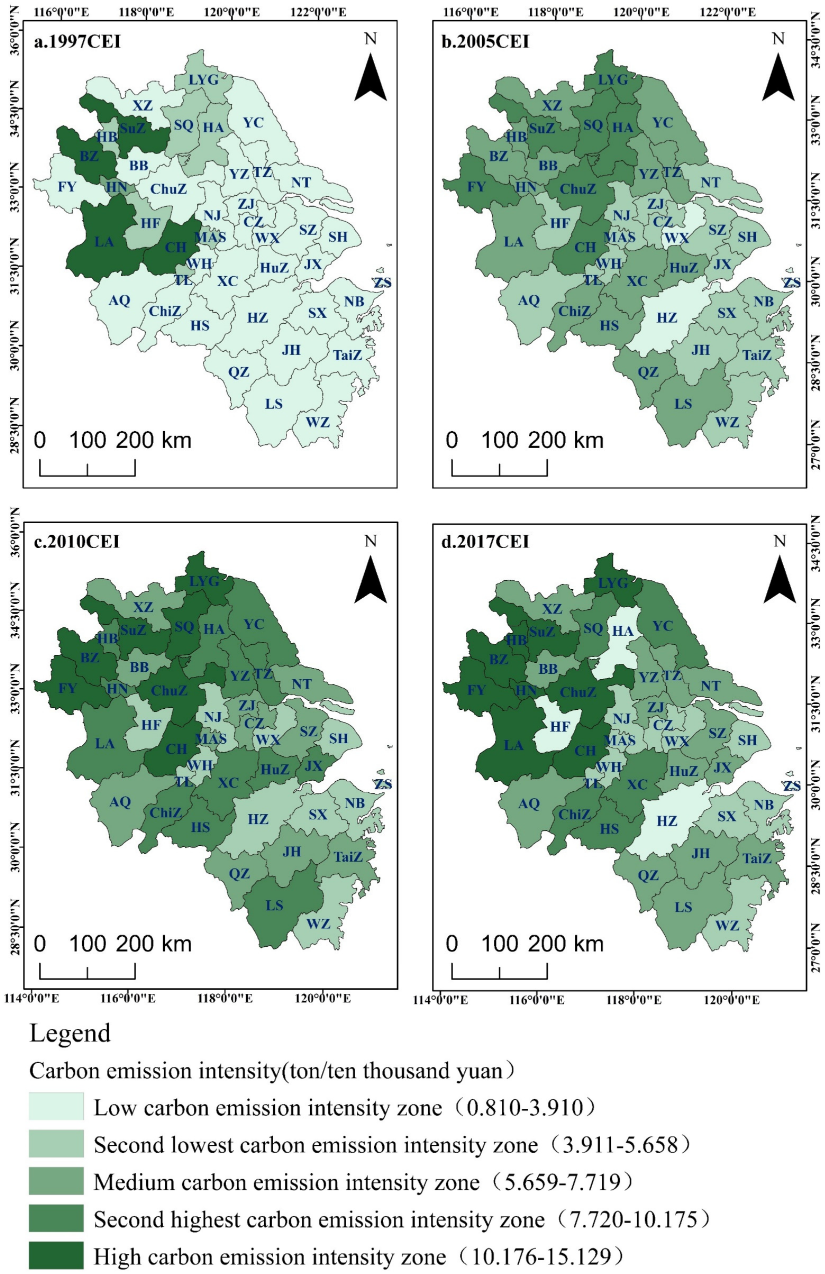

Figure 4. Spatial distribution of carbon emission intensity in the Yangtze River Delta from 1997 to 2017. ((**a**). Spatial distribution of carbon emission intensity in the Yangtze River Delta in 1997; (**b**). Spatial distribution of carbon emission intensity in the Yangtze River Delta in 2005; (**c**). Spatial distribution of carbon emission intensity in the Yangtze River Delta in 2010; (**d**). Spatial distribution of carbon emission intensity in the Yangtze River Delta in 2017).

Figure 4. Geolocation of sample area. Hefei (HF), Wuhu (WH), Chzhou (CZ), Benbu (BB), Huainan (HN), Fuyang (FY), Lu'an (LA), Anqing (AQ), Chaohu (CH), Ma'anshan (MAS), Huaibei (HB), Chizhou (CZ), Tongling (TL), Huangshan (HS), Bozhou (BZ), Suzhou (SZ), Xuancheng (XC), Nanjing (NJ), Suzhou (SZ), Changzhou (CZ), Nantong (NT), Taizhou (TZ), Yangzhou (YZ), Wuxi (WX), Xuzhou (XZ), Lianyungang (LYG), Huaian (HA), Yancheng (YC), Zhenjiang (ZJ), Suqian (SQ), Shanghai (SH), Hangzhou (HZ), Ningbo (NB), Wenzhou (WZ), Jiaxing (JX), Huzhou (HZ), Shaoxing (SX), Lishui (LS), Taizhou (TZ), Zhoushan (ZS), Quzhou (QZ), and Jinhua (JH).

3.2.2. Coefficient of Variation Analysis of Carbon Emission Intensity in the Yangtze River Delta

GS + 9.0 software was utilized to construct the semi-variogram of carbon emission intensity in different years and conduct correlation analysis (Figure 5 and Table 1). According to the variogram graph of 1997, 2005, 2010, and 2017 constructed using a Gaussian model, it can be seen from the graph that the sample points are gradually close to the curve, indicating that the correlation between cities in the Yangtze River Delta is becoming more and more obvious. Cities are also more closely connected and interact with each other. The nugget effect [C_0/C_0 + C] reflects spatial dependence of carbon emission intensity, and the size of the nugget effect reflects the strength of the spatial correlation of carbon emission intensity. The larger the C_0/C_0 + C is, the more dispersed the spatial distribution of carbon emission is, and the weaker the correlation is. As can show in Table 1, R^2 shows an overall increasing trend, and C_0/C_0 + C is 1.22%, 0.07%, 0.21%, and 0.14%, respectively, indicating a strong spatial correlation of carbon emission intensity. Gold block values C_0 are 0.1, 0.002, 0.01, and 0.01, respectively, indicating small errors. Abstention values C_0 + C were 8.23, 3.07, 4.08, and 7.28, respectively, indicating that the sum of random variation and structural variation in carbon emission intensity was small. Although the ratio of the nugget value to the abstention value showed a trend of first decreasing, then increasing and then decreasing, the ratio of nugget value to abstention value was much less than 25%, indicating that the spatial difference of carbon emission intensity in the region was small, and there was a strong spatial correlation. The integration level grew higher and higher, and the improvement of the integration level could significantly reduce the carbon emission intensity of the city [28].

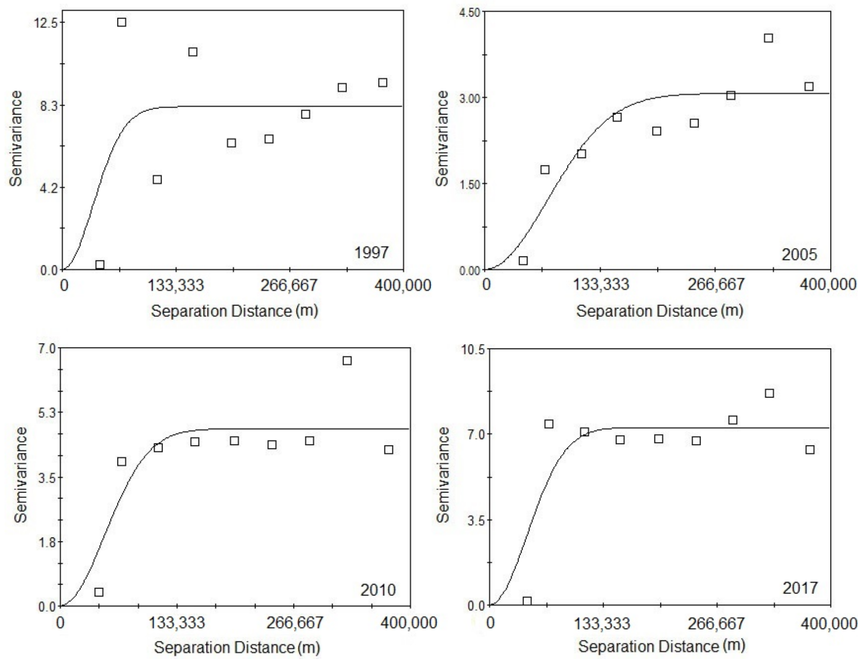

Figure 5. Semi-variance function analysis of carbon emission intensity in the Yangtze River Delta from 1997 to 2017.

Table 1. Semi-variance function analysis parameters of carbon emission intensity in the Yangtze River Delta from 1997 to 2017.

Year	Semivariogram Model	Nugget (C_0)	Sill (C_0 + C)	Nugget/Sill (C_0/C_0 + C)	Coefficient of Determination (R^2)	*p*
1997	Exponential	0.100	8.23	1.22%	0.337	<0.01
2005	Exponential	0.002	3.07	0.07%	0.780	<0.01
2010	Exponential	0.010	4.80	0.21%	0.707	<0.01
2017	Exponential	0.010	7.28	0.14%	0.713	<0.01

3.2.3. Spatial Autocorrelation Analysis of Carbon Emission Intensity in the Yangtze River Delta

GeoDA software was utilized to calculate the global and local Moran's index of carbon emission intensity in the Yangtze River Delta from 1997 to 2017. It can be seen from Figure 6 that the global Moran index of all years is conclusive, and almost all pass the 90% significance test. This indicates that the carbon emissions in the Yangtze River Delta region have an obvious spatial positive correlation, showing a tendency toward a centralized distribution.

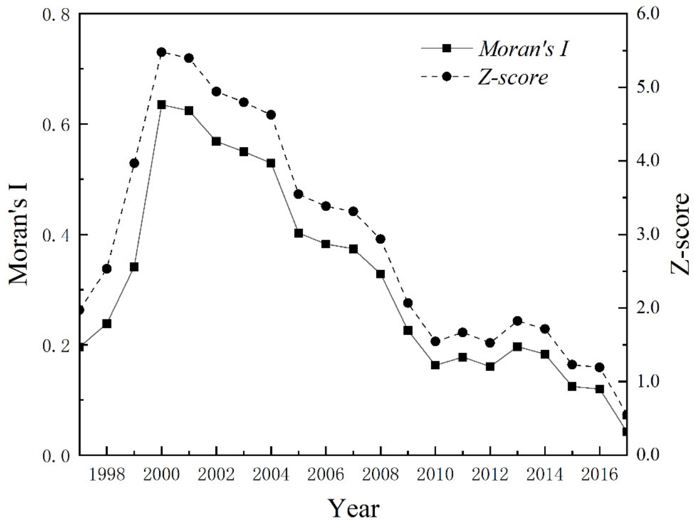

Figure 6. Variation of Moran's index of carbon emission intensity in the Yangtze River Delta from 1997 to 2017.

As can be observed in Figure 6, Moran's index increased significantly from 1997 to 2000, and the spatial aggregation of carbon emission intensity reached its peak in 2000, with a value of 0.64, and then decreased year by year. In 1997, after the 15th National Congress, China implemented the basic policy of "taking the opportunity, deepening the reform, expanding the opening up, promoting development and maintaining stability". With the rapid development of numerous cities, the economy continued to improve, and the carbon emission intensity began to increase continuously; neighboring cities influenced each other and formed a high degree of aggregation. With the arrival of the 12th Five-Year Plan [29], national and local governments have successively issued a series of policies and regulations to guide and standardize the national and local emission reduction and energy conservation work, and the carbon emission intensity has decreased slightly and achieved initial results due to the different carbon emission policies and economic development levels among cities. As a result, the concentration of carbon emission intensity is decreasing year by year in the Yangtze River Delta.

The carbon emission intensity of cities in the Yangtze River Delta has a strong positive spatial correlation. Therefore, the spatial aggregation state and its dynamic evolution law of the carbon emission intensity of cities in the Yangtze River Delta can be further analyzed. The spatial aggregation state distribution of cities in the Yangtze River Delta is given in Figure 7. Figure 7 shows that except for 2017, the carbon emission intensity in the Yangtze River Delta decreases from the north to the south, forming a high aggregation in the north and a low aggregation in the south, showing a significant aggregation state, which is consistent with the spatial autocorrelation of the mineral resources and economic conditions in the north and the south. Cities in coastal areas develop green economies, and the carbon emission intensity is correspondingly reduced. It is a low aggregation state. The comparison of carbon emission intensity from 1997 to 2017 shows that there are noticeable differences in distribution patterns in different years. Since 2005, Suqian City, Xuzhou City, Lianyungang City, and Bozhou City have been at a high level, indicating that the energy consumption and industrial structure of these cities have not been effectively improved, while Hefei, the provincial capital city, has been at a low and high level for a long time. It shows that it has not been able to drive the neighboring cities to decouple economic growth from environmental pollution. Seven cities with low concentrations in 1997 decreased year by year, and there were no cities with a low concentration in 2017. From this, it can be seen that the center of the minimal pattern initially shifted to the north and finally disappeared.

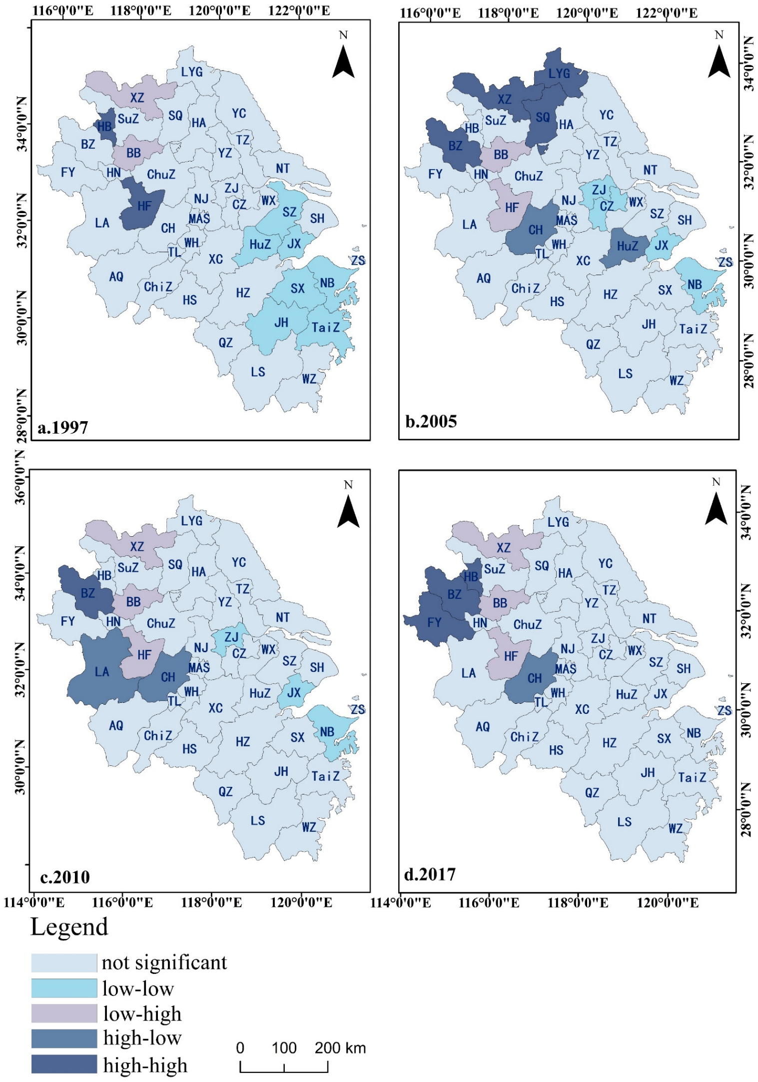

Figure 7. LISA aggregation of carbon emission intensity in the Yangtze River Delta from 1997 to 2017((**a**). LISA aggregation of carbon emission intensity in the Yangtze River Delta in 1997; (**b**). LISA aggregation of carbon emission intensity in the Yangtze River Delta in 2005; (**c**). LISA aggregation of carbon emission intensity in the Yangtze River Delta in 2010; (**d**). LISA aggregation of carbon emission intensity in the Yangtze River Delta in 2017).

3.3. Spatial Differences of the Effects of Factors on Carbon Emission Intensity in the Yangtze River Delta

This paper mainly selects the influencing factors of carbon emission from a population, economy, and technology. Population size, the economic development level, industrial structure, and urbanization degree are taken as the influencing factors to be considered. Through the least square method, it is known that these four driving factors have a significant effect on carbon emissions, and the variance expansion factor (VIF) is less than 10; there is no multicollinearity, so the next step can be calculated.

It can be seen from Figure 8 that, on various indicators, the regression coefficient of population size ranges from −0.462 to 0.171. Population size has a bidirectional effect on carbon emission intensity, but its effect on carbon emission intensity is more inhibitory than promoting. The economic development level has a complete promoting effect on carbon emission intensity, and its average regression coefficient on carbon emission intensity is 0.3674, which shows that the promoting effect is not obvious. The increase in urbanization degree has a two-way effect on carbon emission intensity. The regression coefficient of the urbanization degree ranges from −0.920 to 0.091, and the negative effect is quite strong. The increase in the proportion of the secondary industry in the industrial structure will lead to an increase in carbon emission intensity in general. Its average regression coefficient for carbon emission intensity is 0.1702, so the effect is limited.

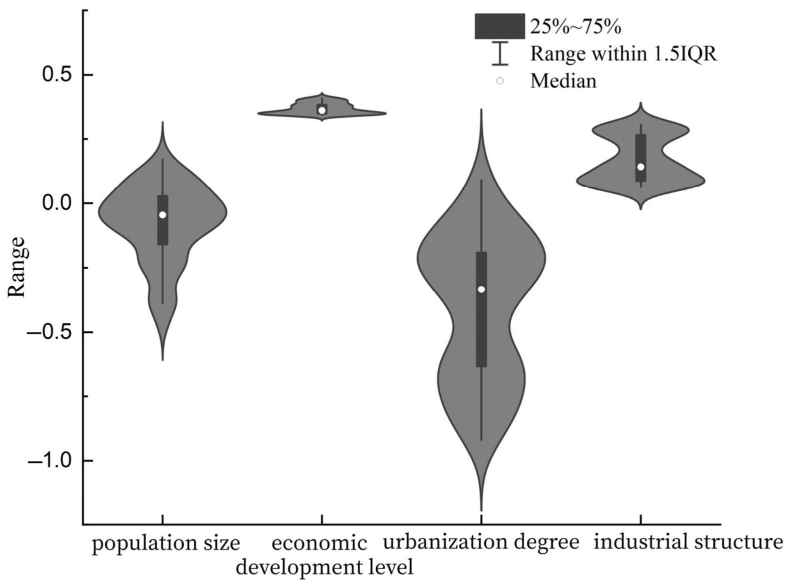

Figure 8. The Violin map of the MGWR Model Analysis of Factors Affecting Carbon Emission Intensity in the Yangtze River Delta.

The MGWR model is utilized to analyze the degree of each influencing factor on the carbon emission intensity of the Yangtze River Delta region, and the influence coefficient (R^2) is visualized with ArcGIS10.2 software.

As is shown in Figure 9, the regression coefficient of population size decreased from northwest to southeast. Population size has a weak positive effect on carbon emission intensity in Fuyang, Bozhou, Huainan, Yangzhou, Yancheng and other inland areas but a negative effect on coastal areas and other cities. As the population gradually converged on the coastal and riverside areas, a situation of high carbonization and high energy consumption was formed, which caused unprecedented pressure on resources and the environment. Therefore, population agglomeration does not possess a positive effect on carbon emission intensity. To a certain extent, the growth of carbon emission caused by the population size effect can be suppressed by improving the utilization rate of population resource sharing and optimizing and adjusting the energy structure [30].

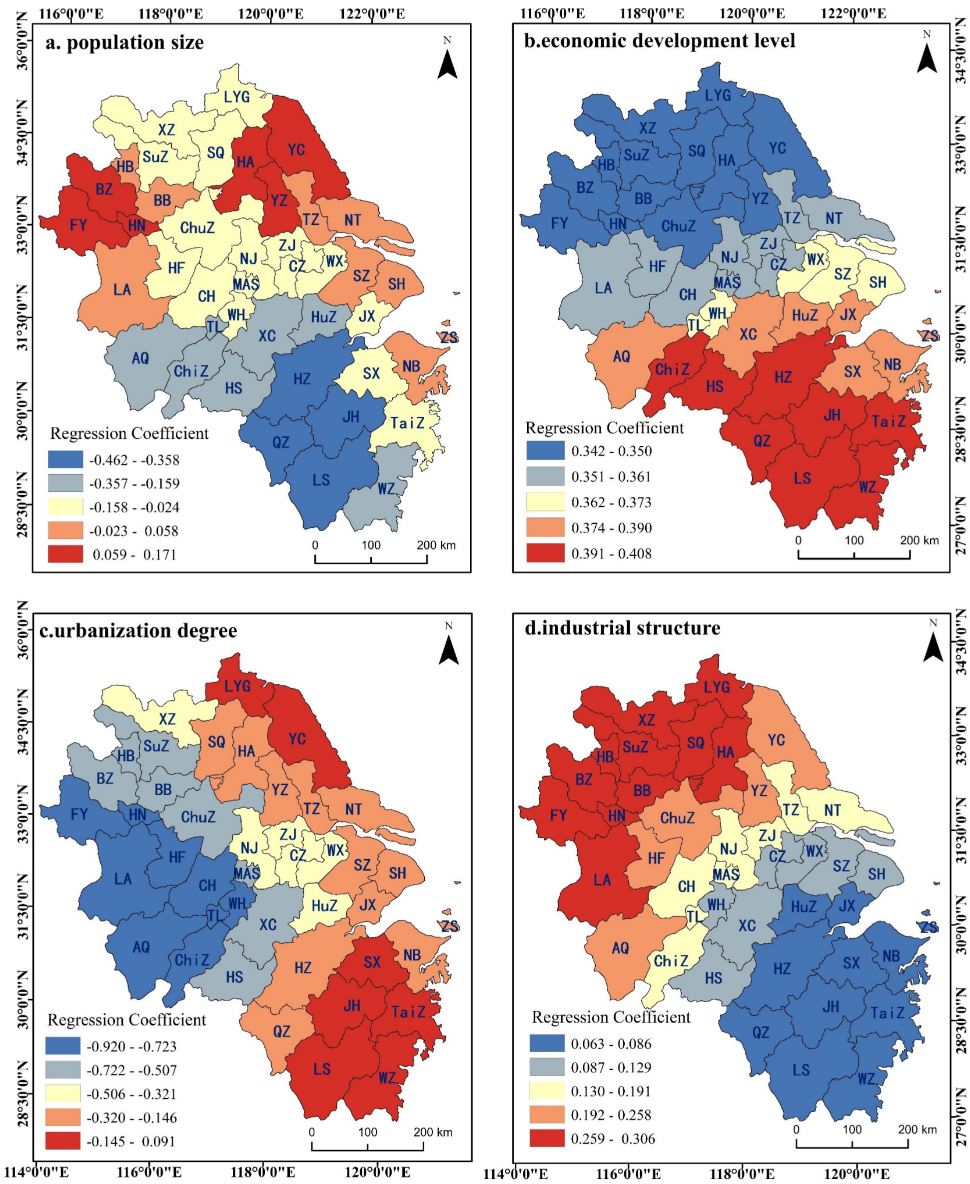

Figure 9. Spatial pattern of multi-scale geographic weighted regression coefficients from 1997 to 2017 in the Yangtze River Delta((**a**). Spatial pattern of regression coefficients of MGWR analysis of population size in the Yangtze River Delta from 1997 to 2017; (**b**). Spatial pattern of regression coefficients of MGWR analysis of economic development level in the Yangtze River Delta from 1997 to 2017; (**c**). Spatial pattern of regression coefficients of MGWR analysis of urbanization degree in the Yangtze River Delta from 1997 to 2017; (**d**). Spatial pattern of regression coefficients of MGWR analysis of industrial structure in the Yangtze River Delta from 1997 to 2017).

The regression coefficient of the economic development level mainly presents a gradient descending pattern from south to north. The level of economic development has the greatest impact on the carbon emission intensity of Hangzhou, Wenzhou, Lishui, and Jinhua, while Xuzhou is the weakest. The integration of economic development and construction in the Yangtze River Delta and a series of economic development driven by the Shanghai Special Economic Zone has accelerated industrial upgrading, but green industrial transformation has not been developed [31]. As a result, the higher the level of economic development, the higher the carbon emission intensity. There is still much room for progress in green, low-carbon and sustainable development.

The regression coefficient of urbanization degree mainly presents a decreasing pattern from northeast to southwest. The degree of urbanization has a weak positive effect on the carbon emission intensity of Lianyungang and Yancheng but a strong negative effect on other cities. The higher the degree of urbanization, on the one hand, the more regional economic development will bring great innovation effect and promote the development of urban green and low carbon economy; on the other hand, with the transformation of new urbanization and low carbon development, the concept of low carbon development of urban residents is gradually deepening. Through the transformation of the urban public governance mode, low-carbon energy structure, low-carbon industry and technology, low-carbon lifestyle, and consumption patterns are promoted to save energy and reduce emissions, thus reducing the impact on carbon emission intensity [32].

From the perspective of spatial distribution characteristics, the regression coefficient of industrial structure mainly presents a gradient descending pattern from north to south. In the north, Fuyang, Huainan, Xuzhou, Huaibei, Lianyungang, Suzhou, and other regions over-rely on the economic benefits brought by the secondary industry, and its industrial structure has a strong impact on the carbon emission intensity of the region. It shows that the increase in the proportion of secondary industry leads to the increase in carbon emission intensity, and the adjustment and optimization of energy structure are the key factors in reducing carbon emission intensity [33].

4. Conclusions

Based on panel data related indicators of the Yangtze River Delta urban agglomeration from 1997 to 2017. This paper uses the dot plot and heat map to analyze the temporal evolution characteristics of carbon emission intensity. The coefficient of variation analysis was utilized to explore the spatial differences of carbon emission intensity in cities in the Yangtze River Delta. Global spatial autocorrelation and local spatial autocorrelation analysis methods were used to verify the spatial correlation degree of carbon emissions among cities in the Yangtze River Delta, and the multi-scale geographically weighted regression (MGWR) model was used to explore the spatial heterogeneity of factors affecting carbon emission intensity, and the following conclusions were drawn:

(1) From 1997 to 2017, the carbon emission intensity of the selected cities fluctuated but generally increased first and then decreased during the sample period. This demonstrates that the Yangtze River Delta region has carried out industrial optimization of industrial development. In recent years, the Yangtze River Delta region has implemented the economic strategy of "green development" to strengthen environmental management. In terms of the overall trend, the carbon emission intensity of Hefei decreased the most, and the absolute value of the decrease reached 0.82 tons/10,000 yuan, indicating that the relevant measures on the carbon emission of Hefei have achieved effective results. However, the carbon emission intensity of Suzhou increased rather than decreased, and the absolute value of the increase reached 3.64 tons/10,000 yuan. However, after reaching the peak, the carbon emission intensity gradually decreased, indicating that although the carbon emission intensity of Suzhou increased significantly during the sample period, it was also effectively controlled. Before 2002, only Hefei's carbon emission intensity was greater than the average of the entire Yangtze River Delta region, but after 2002, all provincial capitals were smaller than the average of the Yangtze River Delta region. This indicates that cities with higher GDP have lower carbon emission intensity and higher levels of low-carbon economic development. Among the 42 cities in the Yangtze River Delta, Huai'an City showed the greatest decrease from 5.17 tons per 10,000 yuan to 0.81 tons per 10,000 yuan, while Fuyang City showed the greatest increase in the absolute value of 10.57 tons per 10,000 yuan.

(2) From 1997 to 2017, the number of regions in the low-carbon emission intensity zones decreased first and then increased, indicating that the carbon emission intensity generally increased first and then decreased during the sample period, and the number of cities in the low-carbon-emission intensity zones and the second-lowest-carbon-emission

intensity zones in the south was much more than that in the north. R2 showed an overall increasing trend. Although the ratio of the nugget value to the abstention value decreased first, then increased and then decreased, the ratio of the nugget value to the abstention value was far less than 25%, indicating that the spatial difference of carbon emission intensity of cities in the Yangtze River Delta decreased and the integration level increased. The global Moran index is positive every year, and almost all of them pass the 90% significance test, indicating that there is an obvious positive spatial correlation of carbon emissions in the Yangtze River Delta, showing a trend of centralized distribution. The spatial aggregation and dynamic evolution of carbon emission intensity in cities of the Yangtze River Delta were further analyzed. Except in 2017, the overall carbon emission intensity in the Yangtze River Delta decreased from the north to the south, forming a high concentration in the northern region and a low concentration in the southern region, showing a significant aggregation state, which is consistent with the spatial autocorrelation of mineral resources and economic conditions in the north and south. Cities in coastal areas develop green economies, and the carbon emission intensity has been correspondingly reduced. It is a low aggregation state. The comparison of carbon emission intensity from 1997 to 2017 shows that there are noticeable differences in distribution patterns in different years. Since 2005, Suqian City, Xuzhou City, Lianyungang City, and Bozhou City have been at a high level, indicating that the energy consumption and industrial structure of these cities have not been effectively improved, while Hefei, the provincial capital city, has been at a low and high level for a long time. It shows that it has not been able to drive the neighboring cities to decouple economic growth from environmental pollution. Seven cities with low concentrations in 1997 decreased year by year, and there were no cities with low concentrations in 2017. From this, it can be seen that the center of the minimal pattern initially shifted to the north and finally disappeared.

(3) Regression coefficients for population size range from −0.462 to 0.171, the effect of population size on carbon emission intensity is bidirectional, but the effect of population size on carbon emission intensity is more inhibiting than promoting. The regression coefficient of population size mainly presents a pattern of decreasing from northwest to southeast. The level of economic development has a maximum promoting effect on carbon emission intensity. The average regression coefficient of the level of economic development is 0.3674, and the promotion effect is not obvious. The regression coefficient of the economic development level mainly presents a gradient descending pattern from south to north. The increase in the urbanization degree has a bi-directional effect on carbon emission intensity. The regression coefficient of urbanization degree ranges from −0.920 to 0.091, and the adverse effect is quite strong. The regression coefficient of the urbanization degree mainly presents a pattern of reducing from northeast to southwest. In general, the increase in the proportion of the secondary industry in the industrial structure will result in the increased carbon emission intensity. The average regression coefficient of the industrial structure is 0.1702, but the effect is restricted, and the regression coefficient of the industrial structure mainly presents a gradient descending pattern from north to south.

This paper analyzes the spatial and temporal pattern evolution of carbon emission intensity and spatial heterogeneity of influencing factors in the Yangtze River Delta from the municipal scale based on the carbon emission panel data and the Statistical Yearbook data of the Yangtze River Delta, which provides a reliable basis for the implementation of targeted carbon emission reduction strategies in the Yangtze River Delta urban agglomeration. However, there are still some problems that have yet to be explored. Firstly, this study is based on the city-level carbon emission data, but if we need to implement regional carbon reduction and emission reduction accurately, we need to carry out research from the county level or smaller scale; secondly, the paper reveals the spatial heterogeneity of the influencing factors of carbon emission intensity in the Yangtze river delta but does not deeply explore the formation mechanism of the spatial heterogeneity of the influencing factors of carbon emission intensity in the Yangtze river delta. Thirdly, because panel carbon emission data are utilized, there are some differences between these data and remote sensing carbon emission data. These issues need to be further explored.

5. Discussion

Based on the above conclusions, this paper proposes discussions and suggestions for further reducing carbon emissions:

(1) Although the total carbon emissions in the Yangtze River Delta show signs of slow growth, the carbon emission intensity has been declining year by year in recent years. Cities in the Yangtze River Delta region have small differences in carbon emissions and a high level of integrated development. Through formulating and implementing sustainable environmental and energy policies, upgrading and optimizing energy consumption structure and industrial structure, the efficient output and transformation and application of green production technologies are promoted.

(2) For a long time, the distribution of carbon emission intensity in the Yangtze River Delta region is not balanced, and the spatial concentration degree decreases year by year and forms a high concentration in the north. Therefore, the formulation of carbon emission reduction policies should consider the implementation of cross-city joint low-carbon measures in high–high-concentration cities in the north of the Yangtze River Delta, improve the shared utilization rate of population resources, promote technological progress and green production together, build an intercity carbon emission reduction coordination mechanism, and form a situation of joint carbon control.

(3) The empirical analysis demonstrates that the population size, economic development level, urbanization level, and industrial structure of the Yangtze River Delta have significant effects on carbon emissions. Owing to China's early implementation of the "family planning" policy and strict control of population structure, population size does not have a strong positive impact on carbon emission intensity. As for the carbon emission problem caused by the level of economic development, the integration of the Yangtze River Delta has the double policy dividend of economic linkage and environmental optimization. It is necessary to fully develop the scale economy effect of urban agglomeration, build the pattern of mutually beneficial and symbiotic coordinated development, and amplify the carbon emission intensity reduction effect of urban agglomeration by deepening integration. The higher the degree of urbanization, on the one hand, introduces a great innovation effect for regional economic development; on the other hand, introduces many environmental pollution problems, making it challenging to achieve green, low-carbon, and high-quality development. The adjustment and optimization of energy structure is the key factor to reducing carbon emission intensity, realizing the gradual replacement of high-polluting energy, and actively exploring the characteristics of zero-emission and low-consumption energy structure, so as to achieve the target of carbon control and emission reduction.

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