

Does Foreign Direct Investment Affect SO₂ Emissions in the Yangtze River Delta? A Spatial Econometric Analysis

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Abstract: As the major source of air pollution, sulfur dioxide (SO₂) emissions have become the focus of global attention. However, existing studies rarely consider spatial effects when discussing the relationship between foreign direct investment (FDI) and SO₂ emissions. This study took the Yangtze River Delta as the research area and used the spatial panel data of 26 cities in this region for 2004–2017. The study investigated the spatial agglomeration effects and dynamics at work in FDI and SO₂ emissions by using global and local measures of spatial autocorrelation. Then, based on regression analysis using a results of traditional ordinary least squares (OLS) model and a spatial econometric model, the spatial Durbin model (SDM) with spatial-time effects was adopted to quantify the impact of FDI on SO₂ emissions, so as to avoid the regression results bias caused by ignoring the spatial effects. The results revealed a significant spatial autocorrelation between FDI and SO₂ emissions, both of which displayed obvious path dependence characteristics in their geographical distribution. A series of agglomeration regions were observed on the spatial scale. The estimation results of the SDM showed that FDI inflow promoted SO₂ emissions, which supports the pollution haven hypothesis. The findings of this study are significant in the prevention and control of air pollution in the Yangtze River Delta.

Keywords: foreign direct investment (FDI); sulfur dioxide (SO₂) emissions; spatial Durbin model (SDM); spatial correlation; Yangtze River Delta

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1 Introduction

After the market-oriented economic reforms were implemented, China quickly became one of the most attractive destinations for foreign direct investment (FDI). As per the World Investment Report, China received U. S. dollars 134 billion of FDI in 2018, ranking third globally (UNCTAD, 2019). FDI promotes the optimization of China's technological level and industrialization. Al-

though the Chinese government has repeatedly stressed that China must spurn the approach of 'treatment after pollution' in capitalist countries, the practice exists in the process of actually using FDI to develop the economy, which worsens the situation of environmental pollution in China (Shen et al., 2017; Zhang et al., 2017).

With the deepening of reform and opening up, FDI has become an important driving force to promote China's economic development. Since 1978, China's

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GDP has maintained an average annual growth rate of 14.56%, becoming the world's second largest economy after the United States in 2010 (Wu, 2016). However, China's economic development is mainly based on the extensive development model with high energy consumption. Although this model can promote the rapid development of China's economy, it is also associated with harmful healthy effects. Even worse, SO₂ emissions have been recognized as an important cause of human respiratory diseases and hence pose a great threat to human health. Furthermore, after escaping into the atmosphere, SO₂ can seriously impede photosynthesis in plants, causing a series of environmental pollution problems such as acid rain and haze. In January 2013, several regions in eastern and northern China encountered the worst haze pollution in history and at least one-seventh of the country was affected by haze, with over 600 million victims (Xu et al., 2019). Public health and environmental issues are increasingly becoming the focus of public attention worldwide.

The Yangtze River Delta is located in the economically developing coastal area of southeastern China. Due to its advantageous geographical position, convenient transportation, and preferential FDI policy, this region attracts significant levels of FDI, which boosts its industrialization (Zhou et al., 2019). The FDI in the Yangtze River Delta reached USD 58.79 billion in 2018, accounting for 43.88% of the country, serving as the engine that supports the sustained development of China's economy. Unfortunately, while FDI has promoted the development of an industrialized economy, environmental pollution has gradually become a more serious problem.

Previous studies have usually adopted the traditional panel regression model to analyze the relationship between air pollution and potential influencing factors, but only a few have considered the effects of spatial correlation. The model assumes that each unit is independent, which means that air pollution emissions and the influencing factors of one region are mutually independent. However, this is inconsistent with reality. On the one hand, emissions of air pollution are transferred from one area to neighboring regions with the flow of air or water, and similarly, the local region is also affected by air pollution emissions from adjacent regions. On the other hand, the industrial agglomeration effects and the

externality environmental regulation may further enhance the spatial correlation of air pollution. In addition, existing studies have confirmed that air pollution has a significant spatial correlation characteristic (Yu et al., 2015; Xu et al., 2017). Thus, if the spatial correlation effects of air pollution between different regions are ignored, the regression results will be biased (Poon et al., 2006). In recent years, the emerging spatial econometric model has been gradually applied to the study of air pollution.

Compared to the traditional panel regression model, the spatial econometrics model introduces spatial factors to analyze spatial dependence and heterogeneity of variables that can effectively avoid the regression results bias caused by ignoring spatial correlation effects (Yang et al., 2015; Chen et al., 2017). For instance, Chen et al. (2019) empirically tested regional differences of spatial spillover and hysteresis effects of haze pollution in China at the national level. However, despite being one of the most important economic regions in China, spatial effects of air pollution in Yangtze River Delta have been rarely investigated.

As the largest comprehensive industrial base in China, the Yangtze River Delta faces great pressure to confront challenge of effectively controlling air pollution against the background of rapid economic development promoted by FDI. Taking 26 cities in the Yangtze River Delta as the research focus for the first time, this paper analyzes the relationship between FDI and SO₂ emissions using a spatial econometric analysis model, which can effectively avoid the estimation bias caused by ignoring spatial correlation effects. The study provides valuable insights for the formulation of future air pollution control policies for the Yangtze River Delta and holds guiding significance for coordinating the relationship between regional economic development and environmental protection.

2 Literature Review

With the rapid increase and extensive flow of FDI worldwide, many scholars have studied the relationship between FDI and air pollution. However, the impact of FDI on the environmental level of host countries has always been the focus of scholars and is still debatable. According to the existing research, the viewpoints of scholars

can be divided into three categories: pollution haven hypothesis (PHH), pollution halo hypothesis, and the compromise theory, which are discussed in details below.

PHH was put forward by [Walter and Ugelow \(1979\)](#). They hold the view that developed countries have higher environmental control standards and pollution control costs, and developing countries have lower economic growth due to lower economic development. Considering requirements including economic development, environmental regulation standards are relatively low in developing countries. Therefore, with the continuous expansion of FDI flows and scale between countries, the pollution-intensive enterprises are transferred from developed to developing countries. Thereafter, more scholars combined theory with empirical evidence to study PHH and provided strong evidence in support ([Hoffmann et al., 2005](#); [Wang et al., 2017](#)). [Wang et al. \(2019a\)](#) asserted that environmental regulation under the condition of an open economy would significantly affect the redistribution of pollution-intensive industries worldwide, thereby triggering the migration of pollution to investment destinations. [Wang et al. \(2019b\)](#) further explained the transfer mechanism of pollution-intensive industries to relatively underdeveloped countries from the perspective of differences in environmental regulation standards. It was found that enterprises in countries with higher environmental standards have obvious competitive advantages compared to those in countries with lower environmental standards, and strict environmental regulations in developed countries force polluting enterprises to migrate to countries with lower environmental standards. Some scholars have tested the output ratio of pollution-intensive enterprises and non-pollution-intensive industries in Latin America, Turkey, and North America. The results reveal that the output ratio of Latin America and Turkey has increased, while the output ratio of North America has continued to decline. This testifies that polluting industries in developed countries migrate to developing countries to avoid strict environmental regulations ([Akboštanc et al., 2009](#)). Furthermore, [Birdsall and Wheeler \(1993\)](#) and [Levinson and Taylor \(2008\)](#) indicated that the FDI inflow would lead to environmental deterioration, supporting PHH.

However, some scholars have pointed out that PHH is not the unique indicator of the relationship between FDI and the host country. They claimed that the FDI inflow

would not lead to deterioration of the host country's environment. On the contrary, the environmental quality of the region can be improved by providing the host country with advanced technologies to promote its realization of clean or green production, which is the pollution halo hypothesis. [Chudnovsky and López \(2007\)](#) found that compared to enterprises in host countries, foreign-funded enterprises tend to implement internationally consistent environmental protection standards and promote the development of environmental protection technologies in host countries, thus producing pollution halo effects. [Eskeland and Harrison \(2003\)](#) believed that transnational corporations based on broad establishment and promotions of global control strategic goals provide host countries with opportunities to learn and adopt green production technologies. Furthermore, they realized the reduction of local environmental pollution was possible by promoting domestic enterprises to adopt uniform environmental protection standards such as ISO14001. [Liang \(2017\)](#) deemed that developing countries could use the technology spillover effects brought by FDI to improve the situation of environmental pollution. [Letchumanan and Kodama \(2000\)](#) revealed that FDI brought by transnational corporations could promote the construction of environmental protection infrastructure of the host country and bring environment-friendly technologies. Besides, these foreign-funded enterprises could better abide by the environmental standards of the host country than domestic enterprises, so that the FDI inflow could reduce environmental pollution. [Mielnik and Goldenberg \(2002\)](#) further pointed out that in the process of cooperating with domestic enterprises, foreign-funded enterprises transfer the technologies that have been eliminated in their own countries but are relatively advanced in the host countries to achieve clean or green production. In addition, foreign-funded enterprises can improve the situation of environmental pollution of the host country by vertical and horizontal spillover effects. [Bakhsh et al. \(2017\)](#) investigated the relationship between FDI growth and economic development, carbon dioxide emissions, and recyclable waste in Pakistan by using the method of simultaneous equations. The results showed that FDI would significantly reduce the emissions of environmental pollution. Other scholars have obtained similar results supporting the pollution halo hypothesis ([Manderson and Kneller, 2012](#);

Asghari, 2013).

In contrast to the above-mentioned two hypotheses that hold opposite opinions, some scholars put forward the compromise theory. They hold that the effect of FDI on the environment is multifaceted and its results depend on the size of the total effect. He (2006) decomposed the influencing factors into scale effect, structure effect, and technical effect when studying the mechanism of FDI impact on environmental pollution. The effect of each factor on environmental pollution depends on the actual situation in different regions. In fact, PHH and pollution halo hypothesis are not distinct, and they can be integrated to some extent. For instance, Jiang et al. (2018) confirmed the coexistence of PHH and pollution halo hypothesis by testing the impact of FDI on environmental pollution. Sheng and Lü (2012) believed that foreign investors might establish enterprises with relatively high pollution levels in the host country that they are investing in, causing pollution to the local environment. At the same time, however, the advanced production technology, management concept, and environmental protection standards of foreign enterprises might improve local environmental protection level. Therefore, the impact of FDI inflow on environmental pollution in the host country ultimately depends on the sum of the effects of various influencing factors.

3 Materials and Methods

3.1 Study area

Yangtze River Delta, located in the alluvial plain before Yangtze River enters the Pacific Ocean, includes Shanghai, Nanjing, Wuxi, Changzhou, Nantong, Yancheng, Yangzhou, Zhenjiang, Taizhou (Jiangsu), Suzhou, Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Jinhua, Zhoushan, Taizhou (Zhejiang), Hefei, Wuhu, Ma'anshan, Tongling, Anqing, Chuzhou, Chizhou, and Xuancheng (Fig. 1). Data obtained in 2017 revealed that this region accounted for 2.21% of China's land, 9.39% of China's population, and more than 21.24% of the country's electricity consumption, and yielded 21.31% of the GDP (NBSC, 2005–2018). According to the air quality status report of China's key regions and 74 cities in 2018, the Yangtze River Delta is among the regions with the highest concentration of air pollution in China (Xiao et al., 2020).

3.2 Spatial analysis methods

(1) Global spatial autocorrelation

Spatial autocorrelation refers to the correlation of the same variable in different spatial positions, which can be used to determine the spatial correlation between different regional economic indicators and to determine the

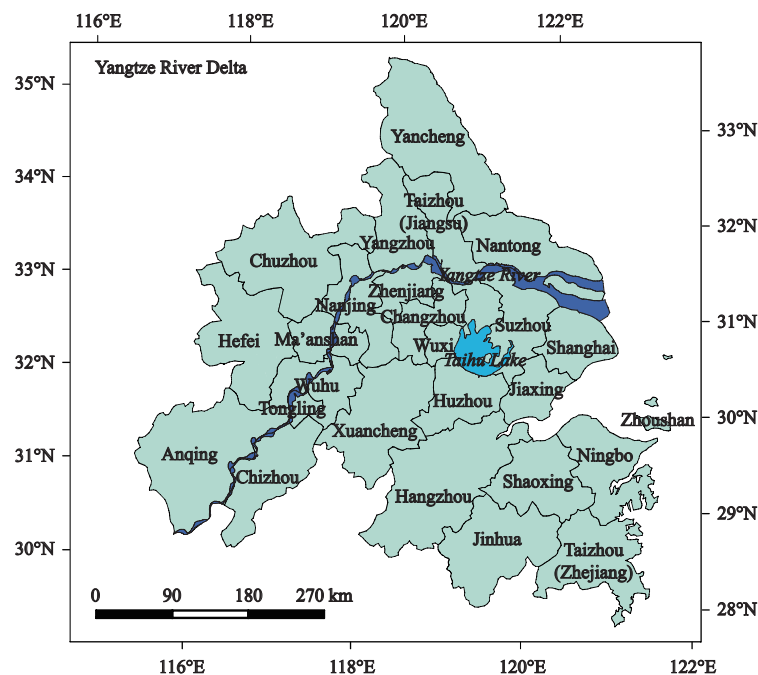


Fig. 1 The location of the Yangtze River Delta

spatial heterogeneity of economic indicators in different regions, such as the gap in economic development, energy efficiency, and environmental regulations, to reveal the regional structure shape of spatial variables (Yang et al., 2019). Previous studies have shown that SO₂ emissions tend to have strong cross-regional and agglomeration characteristics, so the method applies to the spatial correlation test of SO₂ emissions. In this paper, we use the Global Moran's Index (*GMI*) to test the spatial correlation between FDI and SO₂ emissions, which is calculated as follows (Liu et al., 2018):

$$GMI = \frac{n}{\sum_i (x_i - \bar{x})^2} \frac{\sum_i \sum_{i \neq j} W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_i \sum_{i \neq j} W_{ij}} \quad (1)$$

where n represents the number of cities in the study area, x_i and x_j represent the values of the tested variable of city i and city j respectively; \bar{x} represents the average values of the tested variable, and W_{ij} indicates the spatial weight matrix between city i and city j . When the value of *GMI* equals -1 , it means that the variable is completely negatively spatial correlated. When the value of *GMI* equals 0 , it means that the variable has no spatial correlation. When the value of *GMI* equals 1 , it means that the variable is fully positively spatial correlated.

(2) Local spatial autocorrelation

Global spatial autocorrelation can only be used to describe the overall spatial correlation characteristics of FDI and SO₂ emissions in the Yangtze River Delta, which may ignore some atypical features in some areas. Local spatial autocorrelation can reveal the spatial agglomeration of FDI and SO₂ emissions in the attribute values between each unit and its surrounding units, which can demonstrate spatial correlation patterns in different locations (Yu, 2012). Therefore, *Getis-Ord* G_i^* statistics was used to measure the local spatial dependence and heterogeneity of FDI and SO₂ emissions, which is calculated as follows:

$$G_i^* = \sum_{j=1}^{26} W_{ij} x_j / \sum_{j=1}^{26} x_j \quad (2)$$

where n , x_j and W_{ij} have the same meaning as in Equation (1). The $Z(G_i^*)$ value is divided into hot spots, sub-hot spots, cold spots, and sub-cold spots by using the nature break classification method.

(3) Spatial econometrics model

The influence factors of air pollution such as SO₂ emissions were often quantitatively analyzed by establishing regression models. Ordinary least squares (OLS) are one of the most traditional and simplest regression models, which are calculated as follows:

$$Y = X\alpha + \varepsilon \quad (3)$$

where Y represents the dependent variable, X represents the independent variable, α represents the regression coefficient, and ε represents the random error.

The premise of the regression analysis of influencing factors with the OLS method is that each dependent variable is independent in space. However, SO₂ emissions have a significant spatial correlation and dependence, which violates the premise of the OLS method and leads to a bias of regression results. The spatial econometric model can effectively solve this spatial correlation and spatial dependence.

Among common spatial regression models, spatial lag model (SLM) can explain the endogenous dependence of dependent variables, spatial error model (SEM) can explain the interaction effect of error terms, and spatial Durbin model (SDM) can investigate the endogenous dependence of dependent variables and detect the direct and interaction effect of external factors (Zhou et al., 2017). Previous studies have proved that SO₂ emissions have a significant spatial dependence and a certain impact on the environmental level of neighboring regions (Hu et al., 2016). Therefore, the spatial econometrics model can be used to more accurately estimate the effect of various factors on SO₂ emissions, which is calculated as follows:

The SLM is defined as:

$$\ln SO_{2it} = \alpha_0 + \rho \sum_{j=1}^{26} W_{ij} \ln SO_{2it} + \lambda FDI_{it} + \alpha \ln GDP_{it} + \beta \ln IS_{it} + \gamma \ln RD_{it} + \delta \ln PD_{it} + \varepsilon \ln EI_{it} + \theta_{it} \quad (4)$$

The SEM is defined as:

$$\ln SO_{2it} = \alpha_0 + \lambda FDI_{it} + \alpha \ln GDP_{it} + \beta \ln IS_{it} + \gamma \ln RD_{it} + \delta \ln PD_{it} + \varepsilon \ln EI_{it} + \xi_{it}, \xi_{it} = \xi W_{ij} \xi_{it} + \theta_{it} \quad (5)$$

The SDM is defined as:

$$\begin{aligned}
\ln SO_{2it} = & \alpha_0 + \rho \sum_{j=1}^{26} W_{ij} \ln SO_{2it} + \lambda FDI_{it} + \alpha \ln GDP_{it} + \\
& \beta \ln IS_{it} + \gamma \ln RD_{it} + \delta \ln PD_{it} + \varepsilon \ln EI_{it} + \\
& \omega \sum_{j=1}^{26} W_{ij} \ln FDI_{it} + \varphi \sum_{j=1}^{26} W_{ij} \ln GDP_{it} + \\
& \tau \sum_{j=1}^{26} W_{ij} \ln IS_{it} + \sigma \sum_{j=1}^{26} W_{ij} \ln RD_{it} + \\
& \eta \sum_{j=1}^{26} W_{ij} \ln PD_{it} + \psi \sum_{j=1}^{26} W_{ij} \ln EI_{it} + \theta_{it}
\end{aligned} \quad (6)$$

where i and t represent cities and research years, respectively; θ represents random disturbance term; ρ represents spatial auto regression coefficient; ζ represents spatial error coefficient; $\alpha_0, \omega, \varphi, \tau, \sigma, \eta, \psi$ represent spatial regression coefficient of independent variables; and W_{ij} is an element in the adjacency space weight matrix W , representing the spatial correlation between city i and j .

3.3 Indicators and data

In view of the existing literature on FDI and air pollution and considering the availability of data, we selected 26 cities in this region, using China's City Statistical Yearbook from 2005 to 2018 as the database to characterize the pollution level of SO₂ emissions (NBSC, 2005–2018). We took FDI as the explanatory variable of SO₂ emissions and focused on the role of FDI in SO₂ emissions. To minimize the influence of other factors on the dependent variable, we added several control variables to the model, including: industrial structure, research and development investment, population size, and energy intensity. All the indicators are shown in Table 1. The specific definitions of the selected indicators are as follows.

Foreign direct investment (FDI): FDI inflow may have two effects on the environment of the host country.

On the one hand, it may improve the situation of environmental pollution of the host country by promoting technological progress and environmental standards. On the other hand, it may further degrade the local environment by transferring domestic polluting enterprises to the host country. The FDI inflow is represented by the amount of FDI utilized.

Industrial structure (IS): As an important indicator to measure the degree of industrialization, the secondary industry has an important impact on environmental pollution. In the early stages of economic development, the rapid development of secondary industries such as heavy chemical industries greatly increases SO₂ emissions and other pollutants, which then deteriorate the environmental quality. With further development of the economy, the proportion of the output value of secondary industries in the national economy declines, while the proportion of the tertiary industries rises. Therefore, the proportion of the output value of secondary industries in the gross domestic product was selected to represent the industrial structure, to illustrate the impact of the industrial structure on SO₂ emissions.

Research and development investment (RD): The progress of research and development levels can reduce the intensity of comprehensive energy utilization, playing an important role in improving the levels of environmental pollution control and hence reducing emissions of air pollutants. The RD level is expressed by the proportion of science and technology expenditure to public finance expenditure.

Population size (POP): Previous studies have confirmed that population agglomeration leads to the expansion of production scale and industrial specialization agglomeration. On the one hand, the expansion of production scale leads to the increase in resource consumption and pollution. On the other hand, industrial

Table 1 Statistical description of the variables

Variable	Unit	Obs.	Min.	Max.	Mean	SD
SO ₂	10 ⁴ t	364	0.19	51.28	6.98	7.56
FDI	10 ⁶ yuan (RMB)	364	22.57	125001.34	9098.45	16850.26
IS	%	364	27.64	76.00	52.41	8.87
RD	%	364	0.01	12.79	2.75	2.21
POP	10 ⁴ person	364	39.02	1450.00	201.26	258.87
EI	kWh/10 ⁴ yuan (RMB)	364	25.00	29645.48	495.93	1562.44

specialization agglomeration first promotes and later restrains pollution. Population size is expressed by the total population of municipal districts at the end of the year.

Energy intensity (EI): Energy intensity is the reflection of the production process and technology level. Higher energy intensity often means more energy input and pollutant emission. Energy intensity is expressed as the proportion of electricity consumption and total industrial output value.

4 Results

4.1 The global spatial correlation of FDI and SO₂ emissions

Fig. 2 shows the GMI values and the overall change trend of FDI and SO₂ emissions in the Yangtze River Delta from 2004 to 2017, which well reflects the spatial autocorrelation of the two indexes. As shown in Fig. 2, the GMI values of FDI and SO₂ emissions in the Yangtze River Delta were greater than 0 during the study period, indicating that the spatial distribution of FDI and SO₂ emissions in the Yangtze River Delta has a completely positive spatial autocorrelation. Namely, the spatial distribution of FDI and SO₂ emissions expressed spatial agglomeration characteristics. From an overall perspective, the spatial autocorrelation level of FDI showed a rapid decline. The GMI values for FDI decreased from 0.165 in 2004 to 0.014 in 2017. This shows a trend of decreasing spatial concentration of cities in the Yangtze River Delta during the study period. This may be attributed to the fact that FDI first invests in the coastal and riverside cities with convenient transportation and developed economy. Superior physical geography and social and economic advantages are often important factors that attract FDI. In addition, cities in these areas have a higher exposure to the outside world and preferential investment policies, which greatly reduce industrial restrictions on FDI. Inland cities in the Yangtze River Delta have no advantages of physical geography or social and economic development. At the same time, low technological levels, labor productivity, and rate of return on investment have become obstacles to FDI. While with the comprehensive development and increasing openness of the Yangtze River Delta economy, as well as the industrial policy guidance of inland cities, preferential policies for basic

industries, and lower labor costs, FDI is no longer limited to a few developed cities, but has expanded to other regions of the Yangtze River Delta. Therefore, some clusters have disappeared. In contrast to FDI, the spatial autocorrelation level of SO₂ emissions generally presents an upward trend, increasing from 0.133 in 2004 to 0.393 in 2017. Global spatial autocorrelation provides a more holistic understanding of the spatial effects of the relationship between FDI and SO₂ emissions in the Yangtze River Delta from 2004 to 2017. In addition, the average GMI values of FDI and SO₂ emissions during the study period were 0.086 and 0.191, respectively: which indicates that spatial agglomeration was more significant in SO₂ emissions than in FDI. However, global spatial autocorrelation did not show a continuous trajectory of divergence or convergence, although these changes lead to different stages of development.

4.2 The local spatial correlation of FDI and SO₂

We introduced $Z(G_i^*)$ statistics to measure the dependence and heterogeneity of FDI and SO₂ in local space, and divided them into hot spots, sub-hot spots, sub-cold spots, and cold spots according to the results of $Z(G_i^*)$ (Figs. 3, 4).

In Fig. 3, we can see that the spatial distribution of FDI revealed four different clusters. The hot spots remained stable and were always located in Shanghai, Suzhou, and Jiaxing during the study period. The sub-hot spots expanded significantly, with an increase of 120%, among which the stable cities accounted for 45.45%. The sub-cold spots and the cold spots showed fluctuation and decrease from southeast to northwest by 20% and 50%, respectively. From a holistic perspective, the cities represented by Shanghai, Suzhou, and Jiaxing are areas where FDI exhibited hot spots clustering. These

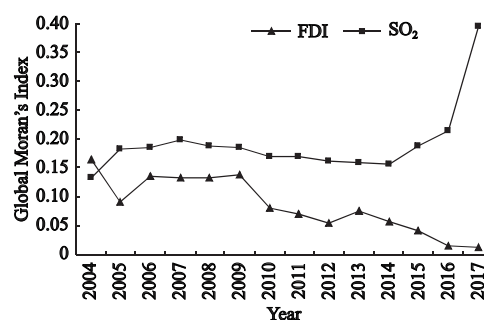


Fig. 2 Global Moran's Index values for FDI and SO₂ from 2004 to 2017 in Yangtze River Delta

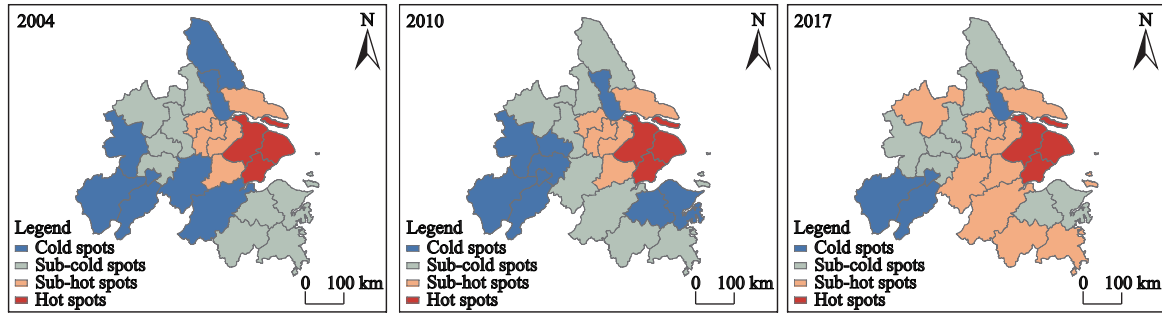


Fig. 3 Spatial distribution of 'hot' and 'cold' spots of FDI of the Yangtze River Delta in 2004, 2010, and 2017

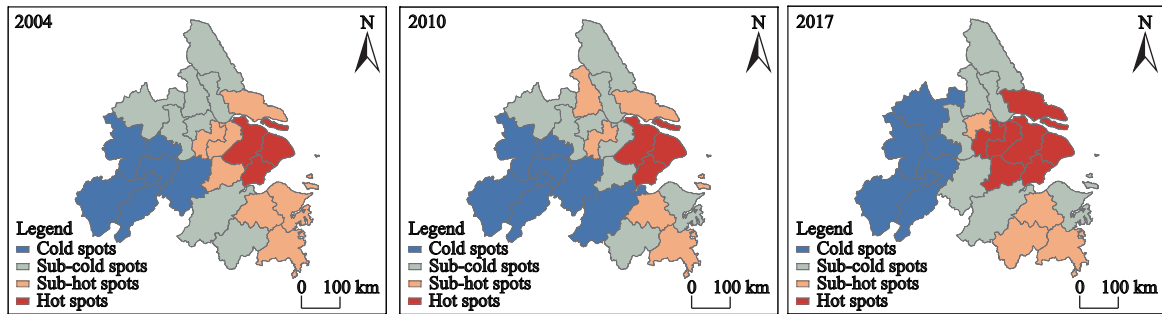


Fig. 4 Spatial distribution of 'hot' and 'cold' spots of SO₂ emissions of the Yangtze River Delta in 2004, 2011, and 2017

cities, as diffusion centers of FDI during the study period have a strong ability to attract FDI. Through exchange and cooperation with surrounding cities, these cities drive the improvement of investment levels in surrounding cities. In the meantime, we can see that Anqing, Chizhou, Tongling, and Taizhou (Jiangsu) are areas where FDI exhibited cold spots clustering. This is mainly because the levels of FDI, demonstration effects, and regional investment are all relatively low in Anqing, Chizhou, and Taizhou (Jiangsu) at present. From these results, we find that the effect of a given city's FDI is closely related to its location and the use of FDI in surrounding areas.

Similarly, we can see from Fig. 4 that the spatial distribution of SO₂ emissions formed four distinct clusters too. The hot spots expanded and were mainly distributed in the estuary area of the Yangtze River Delta, with a growth rate of 133.33%. The sub-hotspots gradually shrank from northwest to southeast, decreasing by 50%. Both the cold spots and sub-cold spots showed a slight expansion trend and were mainly distributed in the central and southwest parts of the Yangtze River Delta. In addition, as the main field of FDI input, the total industrial output value of hot spots in the Yangtze River Delta accounted for 46.96% in 2017, while that of cold spots only accounted for 11.50%. It is clear that the

cause of the difference in the spatial distribution of SO₂ emissions may be the impact of the imbalance of the amount of FDI flowing into the industrial sectors of cities in the Yangtze River Delta.

From the preceding spatial distribution analysis and clusters test of FDI and SO₂ emissions, we can conclude that significant spatial autocorrelation existed in FDI and SO₂ emission levels in the Yangtze River Delta cities during the study period. FDI and SO₂ emissions have obvious path dependence characteristics in line with the Yangtze River Delta geography and form distinct agglomeration areas. Considering the spatial dependence or spatial heterogeneity of geographic data, traditional non-spatial regression methods lead to regression bias (Liu et al., 2013). Therefore, we use a spatial econometric model to estimate the impact of FDI on SO₂ emissions that can effectively avoid such bias.

4.3 Spatial econometric regression results

First, the Hausman test was conducted on the OLS model regression to determine whether a fixed effect or a random effect model should be established. The statistical value obtained was 21.17, and the 1% significance test was passed. Therefore, a fixed effect model was established. Meanwhile, the OLS model was compared with the SLM, SEM, and SDM model. We found that

the R^2 and adjusted R^2 values of SDM were significantly larger, and LM and R-LM both passed the 1% significance test, which further indicated that an econometric model including spatial interaction should be established. In addition, the Wald test and LR test both passed the 1% significance test, indicating that the original hypothesis that SDM can be simplified as SLM and SEM must be rejected, and SDM be selected as the optimal model. Since SDM has three models of time fixed effects, spatial fixed effects, and spatial-time fixed effects, the LR test is adopted to select the model. The results show that the model of spatial-time fixed effects is accepted. Therefore, the SDM with spatial-time fixed effects is the best model, and its parameter estimation results are discussed (Table 2).

Table 2 shows that FDI has a positive impact on SO₂ emissions in the SDM with spatial-time fixed effects,

and the regression coefficient indicates that there is a significantly positive correlation between FDI and SO₂ emissions: an increase in FDI of 1% triggers a 0.225% increase in SO₂ emissions. Meanwhile, spatial spillover effects of adjacent regions on FDI are positive but not significant: an increase in FDI of 1% should lead to a 0.071% increase in SO₂ emissions. It is obvious that the entry of FDI aggravates regional SO₂ emissions, and PHH exists in the Yangtze River Delta.

Among other regression coefficients, the coefficient of IS shows a positive effect on SO₂ emissions, an increase in IS of 1% promotes a 1.034% increase in SO₂ emissions correspondingly. This demonstrates that IS has the greatest impact on SO₂ emissions in the Yangtze River Delta. Spatial spillover effects on adjacent regions on IS shows a significantly positive correlation as well, a 1% increase in IS accompanied by a 1.628% in-

Table 2 Estimation results of the FDI on SO₂ emissions based on the spatial regression model

Determinants	OLS	SLM	SEM	SDM
C	4.508*** (10.393)	—	—	—
$\ln FDI_{it}$	0.213*** (5.910)	0.248*** (7.565)	0.259*** (8.074)	0.225*** (6.723)
$\ln IS_{it}$	1.220*** (5.696)	0.814*** (3.815)	0.752*** (3.576)	1.034*** (4.487)
$\ln RD_{it}$	0.037 (1.260)	0.136*** (2.916)	0.116** (2.411)	0.092** (1.965)
$\ln POP_{it}$	0.490*** (6.728)	0.357*** (5.133)	0.299*** (4.638)	0.397*** (4.909)
$\ln EI_{it}$	0.312*** (6.579)	0.242*** (4.929)	0.225*** (4.639)	0.176*** (3.607)
$W \times \ln FDI_{it}$	—	—	—	0.071 (0.845)
$W \times IS_{it}$	—	—	—	1.628*** (3.444)
$W \times RD_{it}$	—	—	—	0.218** (2.405)
$W \times POP_{it}$	—	—	—	0.099 (0.514)
$W \times EI_{it}$	—	—	—	0.353*** (3.284)
R^2	0.608	0.708	0.689	0.733
Adj- R^2	0.602	0.666	0.655	0.704
Sigma ²	0.291	0.213	0.215	0.194
LogL	288.606	236.420	239.279	218.511
LMlag	66.681***	—	—	—
R-LMlag	12.511***	—	—	—
L-Merr	64.271***	—	—	—
R-LMerr	10.102***	—	—	—
Wald test spatial lag	—	—	—	41.081***
LR test spatial lag	—	—	—	35.818***
Wald test spatial error	—	—	—	48.340***
LR test spatial error	—	—	—	41.536***

Note: Numbers in the parentheses represent *t*-values; *, **, and *** indicate the significance level at 10%, 5%, and 1%, respectively

crease in adjacent regions. This is related to the fact that the economic development of the Yangtze River Delta is shaped by energy-intensive industries, which puts considerable pressure on the reduction of SO₂ emissions. It is worth noting that the impact of RD on SO₂ emissions is significantly positive, and the coefficient implies that an increase in RD results in a 0.092% increase in SO₂ emissions. The spatial spillover effects on adjacent regions on RD are positive too: a 1% increase in RD of adjacent regions leads to a 0.218% increase in SO₂ emissions in adjacent regions. The coefficient of POP is significantly positive for SO₂ emissions; this implies that a 1% increase in POP is accompanied by a 0.397% increase in SO₂ emissions. The spatial spillover effects of POP on adjacent regions are positive but not significant, indicating that a 1% increase in POP is conducive to increase SO₂ emissions by 0.099%. The coefficient of EI was significantly positive for SO₂ emissions: a 1% increase in EI triggers a 0.176% increase in SO₂ emissions. Furthermore, spatial spillover effects on adjacent regions on EI are significantly positive, and a 1% increase in EI of adjacent regions leads to a 0.353% increase in SO₂ emissions in local regions.

5 Discussion

Our study shows that although the GMI values of FDI declined, obvious spatial autocorrelation and spatial dependence exist. The GMI values of SO₂ emissions are significantly positive and increased, which means that the characteristic of spatial autocorrelation and spatial agglomeration is becoming stronger. In addition, from the local spatial autocorrelation estimation results, we can find that the FDI and SO₂ emissions formed spatial clusters at different levels.

SDM with spatial-time fixed effects regression results show that FDI is positively correlated with SO₂ emissions at the 1% level and these results coincide with Baek (2016), who revealed that FDI inflow, will promote SO₂ emissions. The scale effect, industrial structure effect, and technology spillover effect caused by FDI inflow are the main transmission mechanisms that promote the increase of environmental pollutants such as SO₂. First and foremost, the FDI inflow will continue to promote the expansion of regional economic scale and output scale. As a way of reducing production costs and avoiding environmental regulations, foreign-funded

enterprises often have strong motivation to induce local governments to implement more relaxed environmental supervision policies through lobbying and rent-seeking methods. At the same time, the continuous expansion of the economic scale and output scale is bound to consume more fossil fuels, which causes an increase in SO₂ emissions in Yangtze River Delta. Secondly, the FDI inflow changes the regional industrial structure of a region to some extent. Whether the industrial structure changes in the direction of environmental friendliness will depend on the type of FDI attracted by the local government, which is closely related to the level of economic development. Although Yangtze River Delta has a high level of economic development and the quality of FDI is constantly improving, there are large regional differences. As one of the largest industrial bases in China, the second industry with fossil energy is still the main field of FDI attracted by the Yangtze River Delta. The scale expansion of the industrial activities will further increase SO₂ emissions. Finally, FDI will also cause a technology spillover effect on SO₂ emissions. Compared with domestic enterprises in developing host countries, foreign-funded enterprises from developed countries generally have a higher technology levels and greater resource utilization efficiency, which can reduce SO₂ emissions through technology spillover effects. However, for many years, the processing trade in the Yangtze River Delta has mostly adopted the traditional extensive production mode. Loose introduction standards for FDI leads to pollution-intensive industrial agglomeration characterized by of fossil fuels consumption, such that the technology spillover effect generated by FDI does not effectively offset the SO₂ emissions caused by the scale effect and industrial structure effect. Therefore, the rising level of FDI in this region has a significantly positive correlation with SO₂ emissions (Yan and An, 2017).

Furthermore, we found that IS and EI are significantly correlated with SO₂ emissions, which are directly related to the industrial structure and energy consumption structure dominated by fossil fuels in the Yangtze River Delta. The proportion of the secondary industries in Yangtze River Delta decreased from 54.59% in 2004 to 46.38% in 2017 (Zhang et al., 2019). Although the proportion declined, its huge heavy chemical industry with fossil fuels as the main energy source is still the main contributor to SO₂ emissions. Therefore, using

clean energy and adjusting to industrial structure is an efficient and effective means to reduce SO₂ emissions. Besides, POP has a positive impact on SO₂ emissions, indicating that the high density of population may lead to the increase of industrial production scale and energy consumption, which triggers the increase of SO₂ emissions (Wang et al., 2020).

We were surprised to find out that RD has a significantly positive effect on SO₂ emissions, which shows that RD failed to effectively suppress SO₂ emissions. This contradicts the results of Alborno et al. (2014) who believes that high-tech brought by RD can effectively reduce environmental pollution, but it is consistent with the research results of Zhu et al. (2017). The reason for this difference in conclusions may be as follows: On the one hand, there is a significant difference in the proportion of RD expenditure in public finance expenditure among cities in Yangtze River Delta and at a low level, with an average level of 2.75% and a minimum of 0.01%. On the other hand, Yangtze River Delta, one of China's largest industrial bases, shows that its limited RD investment is mainly focused on improving manufacturing productivity, while investment in environmental protection and clean technology is still relatively insufficient. Therefore, instead of suppressing industrial SO₂ emissions, RD promoted the increase in their emissions.

In addition, the coefficient of the lag term in SDM estimation results shows that various factors in adjacent areas also have a corresponding influence on their regions. This is mainly because the economic development level of cities in Yangtze River Delta is closely related, and the import and export activities of products between different cities are frequent. Taking the daily trade mode in Yangtze River Delta as an example, such multilateral trade between different cities leads to a strong spatial spillover effect among regional SO₂ emissions.

This study however, has a few limitations. First and foremost, although our research results show that there are spatial correlation effects of SO₂ emissions between neighboring cities in this study area, we did not analyze the direct relationship between SO₂ emissions from any neighboring cities. Secondly, our research is based on geographical distance matrix and other spatial weight matrices, such as the economic connectivity matrix, which may provide a new perspective for the study of

the impact of FDI on SO₂ emissions. In addition, due to the limitation of data availability, this study failed to carry out the similarities and differences in the impact of FDI on SO₂ emissions from the aspects of the sources of FDI, the amount of FDI inflows into the manufacturing industry, and its spatial differences. Therefore, dynamic panel model data can be used to better understand the spatial relationship between FDI and SO₂ when data is available in the future.

6 Conclusions and Policy Implications

As an important cause of air pollution, SO₂ emissions have a significant impact on human health and socio-economic development, which has attracted extensive attention in academia and policy-making circles. Therefore, it is of great significance to study the driving factors of SO₂ emissions.

In this paper, we first estimated the spatial agglomeration of FDI and SO₂ emissions by using global and local spatial autocorrelation measures. Meanwhile, the fact that existing literature about the impact of FDI on SO₂ emissions often ignores the spatial spillover effects that play a role in this relationship leads to biased estimation results. Therefore, based on the analysis of the traditional OLS model and spatial econometric model regression results, we finally chose SDM with spatial-time effects that can avoid such bias to explore the driving factors of SO₂ emissions. Our results show that FDI can promote SO₂ emissions in the Yangtze River Delta, which supports PHH.

We found several important policy implications based on the research results. To effectively control air pollution caused by SO₂ emissions, the cooperation mechanism of air pollution prevention and control among different cities in Yangtze River Delta should be strengthened. Due to the spatial effects of SO₂ emissions between cities in Yangtze River Delta, SO₂ pollution cannot be solved if there is no cooperation between them. Meanwhile, most of FDI flows into heavy chemical industries and causes serious air pollution. Therefore, it is necessary to investigate further the nature of FDI from the perspective of environmental regulation, actively guide and encourage FDI to flow into environment-friendly industries, and promote the use of cleaner energy to reduce SO₂ emissions at the source. The Yangtze River Delta should also increase the RD invest-

ment in environmental pollution and treatment technology to fully explore the role of RD in improving the situation of air pollution. In addition, megacities like Shanghai should not attempt to reduce SO₂ emissions by merely shifting heavy chemical industrial activities to adjacent cities. Although such an approach can reduce local SO₂ emissions in the short term, they eventually increase SO₂ emissions in neighboring cities and jeopardize local air quality levels.

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