The impact of economic growth on PM$_{2.5}$ concentrations in China’s Yangtze River Delta Urban Agglomeration: Analysis based on Spatial Durbin Model

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Abstract. In the wake of China’s rapid economic development, the contradiction between economic growth and atmospheric environment protection has intensified. Taking Yangtze River Delta Urban Agglomeration (YDUA) as its study area, this paper adopts the prefecture-level data during the period 2003-2016, and employs Spatial Durbin Model to detect spatial autocorrelations of PM$_{2.5}$ concentrations globally and locally and explore the impact of economic growth on PM$_{2.5}$ concentrations in YDUA. Results verified the existence of spatial dependence of PM$_{2.5}$ concentrations in YDUA, and show that there is a N-shaped relationship between the economic growth and PM$_{2.5}$ concentrations in YDUA. Besides, the economic development in local city would impact the PM$_{2.5}$ concentrations in neighbouring cities, the influence trend also making up a N-shaped curve. Policy implications are put forward based on these findings.

1. Introduction
Since reforming and opening-up, China’s economy has grown rapidly, especially in the Yangtze River Delta (YRD) area, which includes Municipality Shanghai and Provinces Jiangsu, Zhejiang, Anhui. This area is one of the fastest-developing regions and plays an important role in China’s economy. During 2003-2016, almost all of the prefecture cities in YRD had an annual economic growing speed of more than 10%, and the speed in cities Taizhou (Jiangsu Province), Hefei and Chizhou were even close to 20%. However, with the quick economic development, increasing environmental pollution in China has caused widespread concern. Haze pollution, dominated by fine particulate matter (PM$_{2.5}$), has befallen many regions in China, and the cities in Yangtze River Delta Urban Agglomeration (YDUA) have suffered severely from the air pollutant. In the Development Plan of Yangtze River Delta Urban Agglomeration in 2016, 26 cities were embraced into YDUA area (as seen in Table 1). According to Greenpeace, only 2 out of 26 cities reached the Secondary standard of PM$_{2.5}$ (35μg/m$^3$) stipulated in the Ambient Air Quality Standard of China, and the PM$_{2.5}$ concentrations in 10 of 26 cities are more than 50μg/m$^3$. The PM$_{2.5}$ pollution has heavily impacted the human health and life. To achieve the harmonious development of economic growth and atmospheric environmental protection in YDUA is needed pressingly. Therefore, it is a matter of cardinal theoretical and practical significance to explore the impact of economic growth on PM$_{2.5}$ concentrations in YDUA.

Many studies demonstrated that economic growth has an indivisible linkage with environment quality. Typical Environmental Kuznets Curve (EKC) hypothesis is utilized in most research, which describes an inverse U-shaped nexus between economic growth and environment pollution. That means as the economy develops, the environment pollution firstly worsens and then gets improved.
Grossman and Krueger, 1994) [1]. Plenty of research findings proved the existence of EKC (Diao et al., 2009; Halkos and Paizanos, 2013) [2-3]. Nevertheless, some studies results are not in support of EKC hypothesis, as other relationships are verified to be present, like U-shaped curve (Ma and Zhang, 2014), N-shaped curve (Akbostanci et al., 2009), and inverted N-shaped curve (Lopez-Menendez et al., 2014) [4-6]. Thus, there is no consistent conclusion regarding the linkage between the economic growth and environment quality under different study period, research area, and econometric techniques. In the majority of existing literature, traditional econometric methods were adopted, and in recent years, spatial econometric technique is employed by some researchers to perform relative studies (Hao and Liu, 2016; Tang et al., 2016) [7-8], but however, the construction of spatial weight matrix still need improvement.

As such, using a prefecture-level panel data set in YDUA during the period 2003-2016, and adopting spatial econometric technique with differentiated spatial weight matrices, this paper aims to explore the spatial dependence of PM2.5 concentrations in YDUA and investigate the relationship between the economic growth and PM2.5 concentrations.

Table 1. The 26 cities in YDUA area

| Province /Municipality | Prefecture-level city |
|------------------------|-----------------------|
| Shanghai               | Nanjing, Wuxi, Changzhou, Nantong, Suzhou, Yancheng, Yangzhou, Taizhou, Zhenjiang |
| Jiangsu                | Hangzhou, Ningbo, Jiaxing, Huzhou, Shaoxing, Jinhua, Taizhou, Zhoushan |
| Zhejiang               | Hefei, Wuhu, Tongling, Anqing, Chuzhou, Ma'anshan, Chizhou, Xuancheng |

2. Methods

In current studies, ESDA technique is adopted to explore the spatial autocorrelation both globally and locally. The global spatial autocorrelation could be described by Moran’s I index, and local spatial autocorrelation could be depicted by Moran’s scatterplot (Anselin, 1995) [9]. The Moran’s I varies from -1 to 1, and when the value is greater than 0, the positive spatial autocorrelation exists, which signifies high-polluted cities are adjacent to cities with heavy pollution, and low-polluted cities are surrounded by cities with similar characteristic. When the value is less than 0, the negative spatial autocorrelation exists, indicating that neighbouring cities have opposite traits of pollution. When the value is close to 0, there exists no spatial autocorrelation. Moran’s scatterplot is made up by four quadrants, with the first and third quadrants showing positive spatial autocorrelation, and the second and fourth quadrants showing negative spatial autocorrelation. Concretely, the first quadrant is featured by high-high agglomeration, the third quadrant is of low-low agglomeration quality, and the second and fourth quadrant are characterized by low-high clustering and high-low clustering, respectively.

As regards the spatial econometric model, SLM (spatial lag model), SEM (spatial error model), and SDM (spatial Durbin model) are most frequently utilized. SLM incorporates the spatial lagged dependent variable, and thus the spatial spillover effect of dependent variable is considered. SEM incorporates the spatial lagged error term, focusing on the spatial dependence stemming from the error shock. SDM consists of both spatial lagged dependent variable and spatial lagged independent variables, considering the impact from not only independent variables of local city, but also the independent and dependent variables of adjacent cities.

The models of SLM, SEM and SDM are depicted by the equations (1)-(3) as below, respectively:

\[ Y = \alpha + \rho WY + X\beta + e \]  \hspace{1cm} (1)
\[ Y = \alpha + X\beta + e = \lambda We + \mu \]  \hspace{1cm} (2)
\[ Y = \alpha + \rho WY + X\beta + \theta WX + e \]  \hspace{1cm} (3)
Where Y is the dependent variable, X represents explanatory variable, W is the spatial weight matrix, ρ, β and θ are regression coefficients, ε is the random error term. As regards equation (3), if θ=0, the SDM could be simplified as SLM, and if θ+ρβ=0, the SDM could be simplified as SEM. Therefore, SDM, as a synthesis of SLM and SEM, is employed in this study. To obtain more accurate results, two spatial weight matrices are introduced into this research, including geographic spatial weight matrix (W1) and economic spatial weight matrix (W2). The geographic spatial weight matrix (W1) is calculated by “inverse distance” method, and the economic spatial weight matrix (W2) takes the proportion of per capita GDP into account on the basis of the “inverse distance” method.

3. Models and data
The STIRPAT model is commonly used to explore the effects of anthropogenic activities on environment (Shao et al., 2016) [10], and is expressed as below:

\[ I_i = aP_i^bA_i^cT_i^d\epsilon_i \]  

Where I represents the impacts on environment, P indicates the population scale, A depicts economic growth level, and T represents technology level; a is the constant term; b, c and d are coefficients related to P, A, T, respectively; e is the error term and i indicates cross-section unit. When logarithmic forms are taken on both sides of equation (4), this equation turns to be the following:

\[ \ln I_i = a + bln P_i + cln A_i + dln T_i + \epsilon_i \]  

In this study, I, P, A and T refer to PM2.5 concentrations, total population, per capita GDP, and technical innovation level. Besides, based on the existing research results and data availability, three other explanatory variables are introduced into the STIRPAT model, namely the secondary industry, the environmental regulation, and the green coverage rate. The detailed descriptions of variables are stated as follows:

(1) Dependent variable
PM2.5 concentrations (pm) is measured by the annual averaged PM2.5 concentrations, and the unit is ug/m³. The data is derived from CIESIN and Battelle Memorial Institute, which is broadly in line with the judgement of China's Ministry of Environmental Protection and local Environmental Protection Departments on the PM2.5 pollution. As seen from Table 2, from 2003 to 2016, the mean, maximum and minimum values of averaged PM2.5 concentrations in samples cities of Jiangsu Province rose obviously. The corresponding maximum value in Anhui Province increased, but the minimum value decreased. By contrast, the PM2.5 pollution situation in Shanghai Municipality and Zhejiang Province eased during the sample period.

Table 2. Sample values of PM2.5 concentrations in 2003 and 2016 (unit: ug/m³)

| District  | Mean 2003 | Max. 2003 | Min. 2003 | Mean 2016 | Max. 2016 | Min. 2016 |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Shanghai | 53.89     | 51.58     | 53.89     | 51.58     | 53.89     | 51.58     |
| Jiangsu  | 55.81     | 58.03     | 58.86     | 62.50     | 50.89     | 54.67     |
| Zhejiang | 37.04     | 31.44     | 54.39     | 50.53     | 25.78     | 21.83     |
| Anhui    | 43.31     | 43.33     | 52.19     | 54.02     | 34.27     | 32.47     |

(2) Independent variables
The total population (pop), per capita GDP (pgdp), and technical innovation level (tec) are adopted to measure the population scale, economic growth level, and technology level. The units of total population (pop), per capita GDP (pgdp) are ten thousand (10⁴) and ten thousand (10⁴) yuan, respectively. The square and cubic forms of per capita GDP are also taken into consideration to enhance the accuracy of this analysis. The data of per capita GDP are calculated at 2003 constant price. Technical innovation level is measured by City innovation index, which is an indicator calculated on the basis of invention patents. Secondary industry (ind) is defined as the proportion of the secondary industry. Environmental regulation (er) is depicted by environmental regulation index, a comprehensive indicator calculated on the basis of the removal rate of industrial sulfur dioxide and the
removal rate of industrial soot and dust (Shen et. al.,2017) [11]. Green coverage rate (green) refers to the rate in urban built-up area. The data are acquired from the China City Statistical Yearbook (2004-2017) and the Report on China’s City and Industry Innovation 2017. As a summary, Table 3 provides the descriptive statistics of above variables.

| Variable | Mean  | Max.  | Min.  | Std. Dev. | Obs. |
|----------|-------|-------|-------|-----------|------|
| pm       | 48.813| 69.825| 21.829| 11.654    | 364  |
| pop      | 475.148| 1500.000| 70.910| 271.638   | 364  |
| pgdp     | 4.140 | 12.444| 0.488 | 2.390     | 364  |
| tec      | 20.803| 541.330| 0.010 | 55.132    | 364  |
| ind      | 52.157| 74.730| 29.830| 7.545     | 364  |
| er       | 1.009 | 10.609| 0.001 | 1.187     | 364  |
| green    | 39.896| 77.780| 5.000 | 5.940     | 364  |

4. Results

4.1 Spatial autocorrelation analysis
The Moran’s I values (as shown in Table 4) are all significant at 1% level under W1 and W2 matrices, indicating that global positive spatial autocorrelation of PM$_{2.5}$ concentrations existed in YDUA from 2003 to 2016. Fig.1 and Fig.2 illustrate the local spatial autocorrelation of PM$_{2.5}$ concentrations under W1 in 2003 and 2016 intuitively, showing that the majority of sample cities in YDUA are distributed in the first and third quadrants. These cities and adjacent cities show similar heavy PM$_{2.5}$ pollution characteristics. In 2016, 12 out of 26 cities were located in the first quadrant, namely Yangzhou, Taizhou (Jiangsu Province), Zhenjiang, Changzhou, Wuxi, Nantong, Suzhou, Yancheng, Hefei, Chuzhou, Ma’anshan, Shanghai. The results suggest that Shanghai Municipality, most cities in Jiangsu Province and some cities in Anhui Province were in high-high agglomeration quadrant. Based on these analysis, the global and local spatial autocorrelation of PM$_{2.5}$ concentrations are testified to be evident in YDUA.

| Year | W1   | W2   | Year | W1   | W2   |
|------|------|------|------|------|------|
| 2003 | 0.166*** | 0.181*** | 2010 | 0.157*** | 0.173*** |
| 2004 | 0.160*** | 0.186*** | 2011 | 0.197*** | 0.215*** |
| 2005 | 0.153*** | 0.181*** | 2012 | 0.163*** | 0.183*** |
| 2006 | 0.193*** | 0.204*** | 2013 | 0.170*** | 0.189*** |
| 2007 | 0.161*** | 0.181*** | 2014 | 0.189*** | 0.214*** |
| 2008 | 0.151*** | 0.174*** | 2015 | 0.183*** | 0.202*** |
| 2009 | 0.170*** | 0.191*** | 2016 | 0.175*** | 0.192*** |

Fig.1. Moran’s I scatterplot in 2003 under W1
4.2 Spatial Durbin Model regression results

Due to the fact that this regression is conducted on specific individuals, fixed effects models are preferable methods (Elhorst, 2003) [12]. In line with the results of LR-tests, spatial-fixed and time-fixed effects models are adopted in this analysis.

As regards SDM, it is imperative to perform Wald test and LR test in advance to confirm whether SDM could be simplified as SLM (H0) or SEM (H0). The Wald and LR tests rejected the two null hypotheses at the 1% level, which verified that SDM is an appropriate model, better than SLM and SEM. The SDM regression results under geographic spatial weight matrix (W1) and economic spatial weight matrix (W2) are presented in Table 5.

As seen in Table 5, the coefficient of W*lnpm is significantly positive at the 1% level. The results suggest that spatial autocorrelation of PM2.5 concentrations is present in YDUA. From the spatial autocorrelation coefficients under SDM, it could be observed that an increase of PM2.5 concentrations in the neighbouring cities by 1% would bring about the augmentation of PM2.5 concentrations in local city by approximately 0.67%. The findings broadly conform to the conclusions drawn from Moran’s I values and Moran’s I scatterplots. The cities suffering from severe PM2.5 pollution in YDUA has high tendency to diffuse the contamination to nearby cities. To tackle the problem of PM2.5 pollution radically, the cities in YDUA should give full consideration to the spatial dependence of PM2.5 concentrations.

Given that the spatial spillover effects existed, the relevant influencing factors would affect the PM2.5 concentrations not only in local city but also in the adjacent areas, and furthermore, the changes of PM2.5 concentrations in neighbouring cities would also work on local city through the feedback effect (Zhang and Li.,2017) [13]. Therefore, the regression coefficients under SDM failed to accurately reflect the actual marginal effects of individual influencing factor on PM2.5 concentrations in local city, namely direct effects. Moreover, the indirect effects refer to the effect of each influencing factor on PM2.5 concentrations in adjacent cities. According to LeSage and Pace (2009) [14], the direct and indirect effects of each independent variable are decomposed as shown in Table 6 and Table 7, under W1 and W2 matrices, respectively.

As regards the direct effects, the coefficients of lnpgdp, (lnpgdp)² and (lnpgdp)³ are positive, negative and positive, respectively, and all of them are statistically significant. There is a N-shaped relationship between economic development and PM2.5 concentrations, and the classic EKC hypothesis is not applicable in YDUA. In the wake of economic development, the PM2.5 pollution in YDUA firstly deteriorated, next alleviated, and then deteriorated. However, it is noteworthy that the coefficient of (lnpgdp)³ is far lower than is lnpgdp, which denoted that the promoting effect of economic development on PM2.5 pollution was trending downwards. In recent years, the rapid economic growth has promoted the expansion of industry scale and the consumption of energy-intensive products, which is a decisive factor for the augmentation of PM2.5 pollution. Thus, the control and governance of PM2.5 pollution in YDUA remains a long-term and tough task.

The direct effects of technical innovation level on PM2.5 pollution are significantly positive in YDUA. Provided that the improvement of technological level is more inclined to production
technology rather than green technology, a higher technical innovation level would probably increase PM$_{2.5}$ pollution (Shao et al., 2016) [10].

As regards the indirect effects, the coefficients of W*lnpgdp, W*(lnpgdp)$^2$ and W*(lnpgdp)$^3$ under W2 matrix are all statistically significant, and the coefficients of W*Intec are significantly positive under W1 and W2 matrices, the spatial spillover effects of the two influencing factors being prominent. The results denoted that local economic development would affect the PM$_{2.5}$ concentrations in adjacent cities, the impact trends making up a N-shaped curve. The higher technical innovation level would worsen the PM$_{2.5}$ pollution not only in local city but also in circumjacent areas. The findings further validated the necessity of conducting spatial econometric analysis.

The direct and indirect effects of total population (pop), secondary industry (ind), green coverage rate (green) and environmental regulation (er) are all statistically insignificant in YDUA, and the directions of coefficients of the first three variables are positive, and the last variable is of negative coefficient. The results indicated that the greening in YDUA was not enough to abate the PM$_{2.5}$ concentrations. The environmental regulation tended to mitigate PM$_{2.5}$ pollution in local city, but as the existing high-emission production mode was difficult to change radically in a short term, the decreasing effect on PM$_{2.5}$ concentrations was insignificant.

Table 5. Results of Spatial Durbin Model

|       | W1             |             | W2             |
|-------|----------------|-------------|----------------|
|      |                |             |                |
| W*lnpm ($\rho$) | 0.675*** (11.560) | 0.672*** (12.237) |
| lnpop | 0.082** (2.020) | 0.086** (2.132) |
| lnpgdp | 0.151*** (3.828) | 0.163*** (4.125) |
| (lnpgdp)$^2$ | -0.052** (-2.269) | -0.059** (-2.504) |
| (lnpgdp)$^3$ | 0.016** (2.190) | 0.017** (2.323) |
| Intec | 0.013 (1.069) | 0.017 (1.469) |
| linind | 0.026 (0.616) | 0.025 (0.591) |
| lner | -0.001 (-0.228) | -0.001 (-0.453) |
| lngreen | -0.003 (-0.149) | 0.001 (0.045) |
| W*lnpop | -0.119 (-0.400) | -0.236 (-0.867) |
| W*lnpgdp | 0.619*** (3.377) | 0.757*** (3.339) |
| W*(lnpgdp)$^2$ | -0.207 (-1.527) | -0.419** (-2.259) |
| W*(lnpgdp)$^3$ | 0.081* (1.652) | 0.131** (2.341) |
| W*Intec | 0.189*** (2.611) | 0.227*** (2.852) |
| W*lind | -0.102 (-0.430) | -0.066 (-0.249) |
| W*lner | 0.006 (0.352) | 0.005 (0.164) |
| W*lngreen | 0.07 (0.460) | 0.097 (0.418) |
| R$^2$ | 0.968 | 0.968 |
| Log-L | 581.816 | 579.816 |

Note: Figures in parentheses are t-statistics. ***, ** and * indicate the significance at 1%, 5% and 10% levels respectively.

Table 6. Spatial Durbin Model Effects Decomposition(W1)

|       | Direct | Indirect | Total |
|-------|--------|----------|-------|
| lnpop | 0.076  | -0.239   | -0.163|
|       | (1.576)| (-0.250) | (-0.166)|
| lnpgdp | 0.227*** | 2.238*** | 2.465*** |
|       | (5.040) | (2.885)  | (3.077) |
| slnpgdp | -0.078** | -0.761   | -0.838 |
|       | (-2.585)| (-1.577) | (-1.664)|
|             | Direct | Indirect | Total |
|-------------|--------|----------|-------|
| trlnpgdp    | 0.026** | 0.287    | 0.313* |
|             | (2.510) | (1.652)  | (1.723) |
| lnintec     | 0.034*  | 0.620**  | 0.654** |
|             | (1.855) | (2.236)  | (2.236) |
| lnind       | 0.018   | -0.274   | -0.256 |
|             | (0.360) | (-0.352) | (-0.316) |
| lner        | -0.001  | 0.013    | 0.013  |
|             | (-0.051)| (0.238)  | (0.220) |
| lngreen     | 0.004   | 0.217    | 0.221  |
|             | (0.145) | (0.440)  | (0.428) |

Note: As in Table 5.

### Table 7. Spatial Durbin Model Effects Decomposition(W2)

|             | Direct | Indirect | Total |
|-------------|--------|----------|-------|
| lnpop       | 0.071  | -0.559   | -0.488 |
|             | (1.568)| (-0.645) | (-0.549) |
| lnpgdp      | 0.241***| 2.700*** | 2.942*** |
|             | (5.056)| (3.030)  | (3.203) |
| slnpdgdp    | -0.100***| -1.415**| -1.515** |
|             | (-3.026)| (-2.142) | (-2.212) |
| trlnpgdp    | 0.030***| 0.437**  | 0.466** |
|             | (2.932)| (2.195)  | (2.262) |
| lnintec     | 0.039** | 0.741**  | 0.780** |
|             | (2.180)| (2.454)  | (2.464) |
| lnind       | 0.018  | -0.227   | -0.208 |
|             | (0.365)| (-0.277) | (-0.246) |
| lner        | -0.001 | 0.015    | 0.014  |
|             | (-0.178)| (0.161)  | (0.146) |
| lngreen     | 0.012  | 0.378    | 0.390  |
|             | (0.373)| (0.521)  | (0.518) |

Note: As in Table 5.

### 5. Conclusions and policy implications

Using the relevant data of 26 cities in China’s Yangtze River Delta Urban Agglomeration (YDUA) over the 2003-2016 period, this study adopted Spatial Durbin Model (SDM) and employed two kinds of spatial weight matrix, namely geographic and economic spatial weight matrices, to detect the global and local spatial autocorrelations of PM$_{2.5}$ concentrations and research the impact of economic growth on PM$_{2.5}$ concentrations in YDUA. The Moran’I values and Moran Scatterplot verified the existence of spatial dependence of PM$_{2.5}$ concentrations in YDUA, and the SDM regression results further confirmed this conclusion. The results of direct and indirect effects decomposition proved that there was a N-shaped nexus between the economic growth and PM$_{2.5}$ concentrations in YDUA. However, the promoting effect of economic development on PM$_{2.5}$ concentrations diminished in the second rising stage of N-shaped curve. Moreover, the economic development in local city would affect the PM$_{2.5}$ concentrations in neighbouring cities, and the influence trend produced a N-shaped curve. Based on the above findings, this study would propose some policy implications to mitigate PM$_{2.5}$ pollution in YDUA as follows.

The first is enhancing the inter-regional joint prevention and control for haze treatment in YDUA. The governments should establish synergetic mechanism, and unify the layout and plan for controlling PM$_{2.5}$ pollution. The second is speeding up the transformation of economic development pattern in YDUA. The local authorities should give consideration to both the quality and quantity of economic development rather than the scale only, set up a green GDP accounting system, and build a resource-
saving and environment-friendly society. The third is promoting progress in green technology in YDUA. The possible measures consist of increasing investment greatly in technology related to haze governance, and setting and implementing relevant policies positively to raise energy use efficiency. The fourth is improving differentiated environmental regulation standards and policies according to the characteristics of socioeconomic development of each city in YDUA. It is imperative to make various forms of environmental regulation work together, including mandatory, market incentive and public voluntary participation. The fifth is expanding greening space. Along with the expansion of built-up area in YDUA, it is difficult to construct large-scale greening space in urban area. In this case, the promoting of three-dimensional greening like vertical greening and roof greening should be highlighted.

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