Regional spatial patterns and influencing factors of Haze Pollution in the Pearl River Delta region

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Abstract. Based on the Pearl River Delta data from 2006 to 2016, this paper uses exploratory spatial data analysis technology to analyze the spatial correlation and spatial cluster characteristics of haze pollution, and uses the Spatial Durbin Model to analyze the influencing factors of haze pollution. The study finds that there is a certain spatial autocorrelation in the spatial distribution of haze pollution in the Pearl River Delta region. The direct, indirect and total effects of energy consumption on haze pollution are not significant, there is an inverted U-shaped relationship between economic development level and haze pollution, population size and industrial structure will increase haze pollution in the local and surrounding areas, technological innovation in the region has a significant impact on local haze pollution and has no significant impact on it in the surrounding areas, and the impact of FDI on haze pollution is not stable in the Pearl River Delta region.

1. Introduction
As one of the most dynamic economic zones in the Asia-Pacific region, the Pearl River Delta (PRD) region is an advanced manufacturing and modern service industry base with global influence[1]. It is also the country with the largest population concentration, the strongest innovation capability and the strongest comprehensive strength[2]. However, with the increasing of the regional economic development and economic strength, the PRD region is also facing serious environmental pollution problems, especially the PM₂.₅ (Fine Particulate Matter) and PM₁₀ (Inhalable Particles) often appear since 2013, which seriously threatens social and economic development and people's health.

In response to air pollution, the Guangdong Provincial Government promulgated the regional air pollution guidance document "Guangdong Pearl River Delta Clean Air Action Plan" in 2010, and promulgated the air pollution joint control plan "Guangdong Province Pearl River Delta Air Pollution Prevention and Control Measures", and striving to make the air quality reach the livable environmental standard by the end of 2020[3]. Under the guidance of this strategy, air pollution control in the Pearl River Delta region has achieved phased results. In 2015, the annual average concentration of PM₂.₅ in the region decreased from 120 micrograms per cubic meter at the highest peak to 34 micrograms per cubic meter, meets the national secondary standard and the World Health Organization level standard, and exceeds the national assessment target two years ahead of schedule[4]. Based on the above, by using exploratory spatial data analysis (ESDA), the paper aims to explore the spatial pattern of haze pollution and the interaction characteristics between neighboring regions and to examine the
influential factors of haze pollution by spatial statistical analysis in the PRD regions of China from 2006 to 2016.

2. Literature Review
Extensive literature confirmed that pollutants can achieve cross-border transmission based on air quality model. Some studies have described the spatial distribution and spatial correlation characteristics of haze pollutant in China based on spatial statistical techniques[5]. Natural factors and socioeconomic factors are important causes of haze pollution. In terms of natural factors, there is a positive correlation between haze pollution and relative humidity and visibility of outdoor air[6]. With the deepening of research, scholars generally believe that socio-economic factors are the decisive factors leading to haze pollution. Summarizing the existing literature, it is found that there are many social and economic factors affecting haze pollution, including backward production technology, high carbon industry structure, energy consumption structure, industrialization and urbanization, the sharp increase of foreign direct investment, fiscal decentralization, urban scale, environmental regulation and rapid economic growth[7]. Tong et al.(2011) believed that rapid economic growth and urbanization led to the increasing of smog emissions[8]. Atici(2012) found that trade openness exacerbated haze pollution. Bastola and Sapkota(2015) explored that the occurrence of haze pollution was the result of various factors such as industrialization-based industrial development model and coal-based energy consumption structure[9].

The existing research pays more attention to the factors affecting haze pollution at the national level, and the existing research less considers the spatial correlation characteristics of haze pollution, and adopts the general econometric method to carry out empirical analysis. Therefore, it is necessary to further consider the impact of various factors on the haze pollution in the PRD region from a more comprehensive and in-depth perspective, and then provide a reference for haze pollution control.

3. Research Design

3.1. exploratory spatial data analysis (ESDA)
The exploratory spatial data analysis method can be used to describe the spatial distribution characteristics and spatial correlation of each variable, which mainly includes Global Spatial Autocorrelation and Local Spatial Autocorrelation, and equations 1 and 2 show the calculation methods of the two, respectively.

\[
I = \frac{n}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (x_i - \bar{x})(x_j - \bar{x}) = \frac{n}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} x_{ij} (x_i - \bar{x})(x_j - \bar{x}) \quad (1)
\]

\[
\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i = \frac{(x_i - \bar{x}^2) \sum_{i=1}^{n} W_{ij} (x_i - \bar{x})}{\sum_{i=1}^{n} W_{ij}} \quad (2)
\]

Where I and II are global and local spatial autocorrelation values, n is the number of spatial unit data, Xi and Xj represent the attribute values of spatial units i and j, respectively, and Wij is the spatial weight coefficient matrix, indicating the spatial unit neighboring relationship. This paper adopts geographic adjoining spatial weight matrix(W1) and geographic distance matrix(W2).

3.2. Model Building and Variable Selection
Based on the IPAT model, environmental pressure, population, wealth and technical level, energy consumption (EC), the total population at the end of the year (PO), the per capita GDP, industrial structure, technological innovation level(R&D) and foreign direct investment (FDI) are considered in the model. The panel data of this model is set as follows:

\[
\ln PM_{it} = \gamma \ln PM_{it-1} + \beta_1 \ln IS_t + \beta_2 \ln PO_t + \beta_3 \ln GDP_t + \beta_4 \ln R & D_t + \gamma W \ln EC_t + \lambda W \ln PO_t + \theta W \ln GDP_t + \theta W \ln IS_t + \theta W \ln FDI_t + \theta W \ln R & D_t + \mu_t + \lambda + \epsilon_t \quad (3)
\]

Where, i represents provinces; t represents the period, lnPM10 refers haze pollution. LnPM10 means haze pollution. lnPM10t is the spatial lag term of the explained variable (haze pollution), \( \partial \)
The spatial lag coefficients. $wlnEC_{it}$, $wlnPO_{it}$, $wlngdp_{it}$, $wln2gdp_{it}$, $wlnIS_{it}$, $wlnFDI_{it}$, $wlnR&D_{it}$ are the spatial lag term of explanatory variables. $\mu_i$, $\lambda$, $\varepsilon_{it}$ are the area effect, time effect and random disturbance term respectively. $\varepsilon_{it}$ obeys normal distribution. $w_{ij}$ is the spatial weight matrix. $\lnEC$, $\lnFDI$, $\lnIS$, $\lnPO$ and $\lnR&D$ means energy consumption, foreign direct investment, industrial structure, population size and technological innovation level respectively. $\ln\text{gdp}$ and $\ln^2\text{gdp}$ represent the first and second terms of per capita GDP respectively. $\text{PM10}$ is used as a measure of haze pollution and $\text{PM2.5}$ is used as a confirmatory analysis, and the data comes from the report of “Guangdong-Hong Kong Pearl River Delta Regional Air Monitoring Network”. Energy consumption is measured by total coal consumption in each region, and the actually amount of used foreign capital of each province is used to measure the level of investment introduction[1]. Industrial structure is measured by the proportion of the secondary industry in GDP, population size and technological innovation level are measured by the total population and research and experimental development funding respectively[1]. Gross Domestic Product (GDP) is indicated by actual GDP per capita. The data in this paper are mainly from the “Guangdong Province Statistical Yearbook”.

4. Results

4.1. Spatial Correlation Analysis of Haze Pollution in the Pearl River Delta
Figure 1 reports the trend of global spatial autocorrelation values for haze pollution in the Pearl River Delta region from 2006 to 2016. It can be seen from Fig. 1 that the lowest Moran’s I value is -0.280418 in 2008, and the highest value is 0.475183 in 2013. Except the years of 2007, 2008 and 2012, the global Moran’s I value are positive and ranges from 0.04666 to 0.4751, which implies that haze pollution has a certain spatial autocorrelation in the Pearl River Delta region. Figure 2 showed the Moran scatter plot of haze pollution in the Pearl River Delta in 2006, 2011 and 2016. During the observation year, the Moran scatters in more than half of the Pearl River Delta region are distributed in the first and third quadrants. In 2006 and 2011, there are 5 regions in the first and three quadrants, and 4 regions are located in the first and three quadrants in 2016, which proves that there is a certain spatial autocorrelation in the spatial distribution of haze pollution in the Pearl River Delta region.

![Figure 1 Trends in the global Moran’s I value of haze pollution in the PRD region from 2006 to 2016](image1)

![Figure 2 Moran scatter plot of haze pollution in the Pearl River Delta in 2006, 2011 and 2016](image2)
4.2. Analysis of Factors Affecting Haze Pollution in the Pearl River Delta

It is found that the hausman statistical value is 12.7633 and the degree of freedom is 15, P The value is 0.6295, which indicates that the random effect model is more explanatory power, the random effects model is used to conduct empirical analysis, and the Spatial econometric test results are listed in Table 1.

Table 1. Spatial econometric test results

| Variables | W1        | W2        |
|-----------|-----------|-----------|
| intercept | -67.8238**** | -74.4973**** |
| EC        | 0.3629**  | -0.0753   |
| lnPO      | 0.2304**** | 0.2039**** |
| lnpgdp    | 5.5052**** | 2.5198**  |
| ln2pgdp   | -0.2515**** | -0.1147   |
| LnIS      | -0.4688*** | -0.2976*  |
| lnFDI     | -0.0726**  | -0.1043** |
| lnR&D     | -0.0320*** | -0.0405**** |
| w*EC      | -0.7687    | 1.4825    |
| w*lnPO    | -0.1500    | 0.4212*** |
| w*lnpgdp  | 9.9032**** | 12.4749*** |
| w*ln2pgdp | -0.4777**** | -0.5669*** |
| w*lnIS    | -1.8444*** | -1.9259*** |
| w*lnFDI   | -0.0347    | 0.0520    |
| w*lnR&D   | -0.0133    | 0.0076    |
| W*dep.var.| 0.4079**** | 0.3600**** |
| Adjusted R² | 0.5814 | 0.6343 |
| Log likelihood | 59.3286 | 60.1084 |

Note: ****, ***, ** and * indicate the significance at 1%, 5%, 10% and 20% level, respectively.

First, the coefficients of W*dep are 0.4079 with the geographic adjoining spatial weight matrix (W1) and 0.3600 with the geographic spatial weight matrix (W2), both pass the significant test at 10%, which indicates that haze pollution has significant spatial correlation characteristics. Second, the impact of energy consumption on haze pollution is significant in the model with geographic adjoining spatial weight matrix, but the impact is not significant in the model with geographic distance weight matrix model, which indicates that the impact of energy consumption on haze pollution is unstable. Population size has a significant effect on haze pollution at the 1% significance level in the case of W1 and W2, and population size has increased the haze pollution from the coefficient symbol. Per capita GDP, FDI and technological innovation have an important effect on haze pollution at the 10% significance level in the case of W1 and W2, from the coefficients symbol it is found that Per capita GDP increased haze pollution, but FDI and technological innovation effectively inhibited haze pollution. Industrial structure has an effect on haze pollution at a 20% significance level. Population size has a significant effect on haze pollution at the 1% significance level in the case of W1 and W2, and population size has increased the haze pollution from the coefficient symbol. Per capita GDP, FDI and technological innovation have an important effect on haze pollution at the 10% significance level in the case of W1 and W2, from the coefficients symbol it is found that Per capita GDP increased haze pollution, but FDI and technological innovation effectively inhibited haze pollution. Industrial structure has an effect on haze pollution at a 20% significance level. Population size has a significant effect on haze pollution at the 1% significance level in the case of W1 and W2, and population size has increased the haze pollution from the coefficient symbol. Per capita GDP, FDI and technological innovation have an important effect on haze pollution at the 10% significance level in the case of W1 and W2, from the coefficients symbol it is found that Per capita GDP increased haze pollution, but FDI and technological innovation effectively inhibited haze pollution. Industrial structure has an effect on haze pollution at a 20% significance level.
at the 20% significance level in the case of W1 and W2, which means industrial structure will increase haze pollution in the surrounding areas. The total and direct effects of FDI on haze pollution are not significant in the case of W1 and W2, which means the effect is not stable. The direct and total effects of technological innovation on haze pollution are significant, and the indirect effects are not significant in the case of W1 and W2, which means technological innovation in the region has a significant impact on local haze pollution and has no significant impact on it in the surrounding areas.

Table 2. Direct effect, indirect effect and total effect of spatial durbin model

| Variables | Total effect | Indirect effect | Direct effect | Total effect | Indirect effect | Direct effect |
|-----------|--------------|----------------|--------------|--------------|----------------|--------------|
| EC        | -0.7059      | -0.9587        | 0.2529       | 2.3147       | 2.2636         | 0.0511       |
| lnPO      | 0.1537       | -0.0710        | 0.2247****** | 1.0130***    | 0.7638**       | 0.2491****   |
| lnpgdp    | 25.9780****  | 18.4743***     | 7.5036****** | 23.77060***  | 20.03320***    | 3.7374**     |
| ln'pgdp   | -1.2300****  | -0.8829***     | -0.3471******| -1.0802***   | -0.9100***     | -0.1702**    |
| LnIS      | -3.9120****  | -3.1087***     | -0.8033****  | -3.6294***   | -3.1381****    | -0.4913*     |
| lnFDI     | -0.1895      | -0.1044        | -0.0851      | -0.0552      | 0.0443         | -0.0995**    |
| lnR&D     | -0.0792**    | -0.0418        | -0.0375***   | -0.0760*     | -0.0338        | -0.0422***   |

Note: ****, ***, ** and * indicate the significance at 1%, 5%, 10% and 20% level, respectively.

4.3. Robustness test

The robustness test was performed by using pm2.5 as surrogate variable, and table 3 showed the results. As can be seen from Table 3, the coefficients of W*dep are all significant at the level of 1%, the total effects of energy consumption, population size, industrial structure, FDI and technological innovation on haze pollution are significant in the case of W1 and W2, and the results of the empirical study are verified again.

Table 3. The results of robustness test

| Variables | Total effect | Indirect effect | Direct effect | Total effect | Indirect effect | Direct effect |
|-----------|--------------|----------------|--------------|--------------|----------------|--------------|
| EC        | 3.2532**     | 3.04473***     | 0.2085       | 2.4078       | 2.8373*        | -0.4294**    |
| lnPO      | 0.3613**     | 0.1841         | 0.1773***    | 1.2288**     | 0.9951**       | 0.2337****   |
| lnpgdp    | 32.4968****  | 26.0962***     | 6.4006******| 22.8376**    | 19.6590**      | 3.1867**     |
| ln'pgdp   | -1.4438***   | -1.1578***     | -0.2860******| -1.0461***   | -0.9002**      | -0.1460**    |
| LnIS      | -5.6565****  | -4.6974***     | -0.9592******| -6.0508***   | -5.2360****    | -0.8148****  |
| lnFDI     | -0.8357***   | -0.6416***     | -0.1942******| 0.8699**     | 0.9042***      | -0.0342      |
| lnR&D     | -0.1339**    | -0.1066**      | -0.0273**    | -0.1559***   | -0.1251**      | -0.0308***   |
| W*dep.var.| 0.7850****   | 0.7450****     | 0.6428       | 124.4409     |

Note: ****, ***, ** and * indicate the significance at 1%, 5%, 10% and 20% level, respectively.

5. Conclusions

Based on the Pearl River Delta data from 2006 to 2016, this paper uses exploratory spatial data analysis technology to analyze the spatial cluster characteristics of haze pollution, and uses the Spatial Durbin Model to analyze the influencing factors of haze pollution. The study finds that the global Moran’s I value are positive and ranges from 0.04666 to 0.4751, except the years of 2007, 2008 and 2012, and the coefficients of W*dep pass the significant test at 10%, which indicates that haze pollution has significant spatial correlation characteristics. The effects of energy consumption on haze pollution are not significant, and the effect of FDI on haze pollution is not stable. The direct, indirect and total effects of per capita GDP and the square of per capita GDP on haze pollution are significant, the level of economic development in the region has an important impact on haze pollution in the
region and surrounding areas, and there is an inverted U-shaped relationship between economic development level and haze pollution. The direct, indirect and total effects of population size and industrial structure on haze pollution are significant, and they will increase haze pollution in the surrounding areas. Technological innovation in the region has a significant impact on local haze pollution and has no significant impact on it in the surrounding areas.

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