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RESEARCH ARTICLE

Do economic development and population agglomeration inevitably aggravate haze pollution in China? New evidence from spatial econometric analysis

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Abstract

With sustained economic development, China's ecological environment is becoming increasingly fragile and the problem of haze pollution is becoming increasingly prominent, which has affected the normal life of human beings and the stable development of society. In this paper, 287 cities' panel data from 1998 to 2016 are used, $PM_{2.5}$ is used to represent haze pollution, and the spatial Durbin model is used to explore the role of the economy and population agglomeration on smog pollution. The empirical results show that (1) haze pollution has obvious spatial spillover. From the perspective of China as a whole, the relationship between the economy and smog pollution is an inverted U shape. (2) China is divided into three economic regions, i.e., the east, the middle, and the west. In the east and middle regions, it is found that economic development also shows an inverted U-shaped relationship with haze pollution. (3) Regardless of the country or the three major economic regions, population agglomeration is the primary factor that aggravates haze pollution; the progress of technology and the optimization of the industrial structure can improve haze pollution. (4) Through further analysis of the indirect effects of haze in China, it is found that there is a significant spatial spillover effect. According to the results of this research, policy suggestions are put forward.

Keywords Spatial Durbin model · $PM_{2.5}$ · Economic development · Haze pollution · Spatial correlation

Introduction

Since 2013, the problem of smog pollution, the major particular component of which is $PM_{2.5}$, has become increasingly serious, which seriously affects public health and daily life. According to the data from a bulletin reporting on the state of China's ecological environment published by the government in 2017, the air conditions of 338 cities above the prefecture level have been tested in China, of which 239 cities have exceeded the standard, and polluted weather accounts for 70.7% of the total weather. Polluted days with $PM_{2.5}$ as the main particular component account for 74.2% of polluted days, and weather with PM_{10} as the main particular component accounts for 20.4% of weather. According to a report on the cost of pollution released by the World Bank in 2016, air pollution has become a risk factor for premature death.

Haze has threatened public health and normal life and caused huge losses to the economy, which have aroused widespread concern from the state, the society, and the public. In 2013, the Chinese government issued an "Air Pollution Control Action Plan," which proposed to strengthen the comprehensive treatment of air pollution, strictly supervise the discharge of pollutants, accelerate the upgrading and optimization of industrial structures, and eliminate industries with high pollution and backwardness. In 2017, Premier Li Keqiang first puts forward the concept of "defense against the blue sky," which mandated strengthening the management of the ecological environment, improving the current atmospheric environment, and realizing the requirements of sustainable development. According to the report of the Nineteenth National Congress of the Communist Party of China, at present, the problem of air pollution in China is still prominent. China should continue to carry out air pollution

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prevention and control actions to win the battle of blue sky protection.

Since the implementation of reform and opening-up in 1978, China's economy has gradually developed and accomplished extraordinary achievements. China's position in the world has become increasingly prominent, and its comprehensive economic strength ranks among the highest in the world. However, during the sustainable economic development process, the accelerated urbanization produced a large amount of dust from an increase in per capita income and the increase in the number of public cars, resulting in traffic congestion and more automobile exhaust emissions. Through economic development, China's investments in innovation increased, encouraging enterprises to invent new green environmental protection technologies and improving the utilization rate of technologies, thus reducing haze pollution. In addition, with increasing population size, human demand for energy is improving, resulting in a shortage of land resources. The haze problem is becoming serious; however, population agglomeration can improve the utilization rate of public resources and reduce environmental pressure. Therefore, an exploration of the relationship between economic development and haze pollution and how economic development affects haze pollution shows that the impact degree and direction of population agglomeration on haze pollution are conducive to the coordinated development of economy and environment. Moreover, an exploration of the relationship among economic development, population agglomeration, and haze can provide the basis for the reasonable formulation of policies and haze pollution measures.

Many scholars have studied problems related to haze pollution. At present, research mainly focuses on the composition, formation mechanism, and meteorological causes of haze particles, with few studies focusing on economic and social factors. In addition, haze pollution is diffuse, which means that haze is not an independent variable in space, and the traditional measurement method is no longer used in this study. Therefore, this paper considers the spatial spillover effect of haze pollution and uses a spatial econometric model to explore the impact of the economy and population agglomeration on haze pollution. In terms of data selection, this paper takes $PM_{2.5}$ as the measurement index of haze and uses urban panel data from 1998 to 2016 for the research.

Literature review

Haze, a combination of fog and haze, has become a major concern of the public in recent years. The main particular component of haze is $PM_{2.5}$. At present, in the study of $PM_{2.5}$, some articles study the source and components of $PM_{2.5}$ from the perspectives of chemistry and meteorology, as well as perform a risk assessment of $PM_{2.5}$ on human health. Li et al. (2019b) conducted a sampling survey using the gas chromatography-mass spectrometry method. The main components of $PM_{2.5}$ are NPAHs and OPAHs, the main source of which is coal combustion. In winter, NPAHs and OPAHs are significantly higher than in other seasons. Huang et al. (2014) used a quartz fiber filter (QFF) membrane and polyurethane foam (PUF) to collect samples to study the toxicity of these substances and their derivatives. The toxicity of the derivatives of NPAHs and OPAHs is worse than that of the parent substances. In addition, Ma et al. (2016a) used the positive matrix factorization (PMF) model to study NPAHs and OPAHs. The results showed that the emission of automobile exhaust and coal combustion are the main causes of pollution. Lu et al. (2019) studied $PM_{2.5}$ in the Pearl River Delta of China, showing that this region was the main contributor of $PM_{2.5}$.

Scholars have studied the source and composition of $PM_{2.5}$ in different countries and regions, including France (Albinet et al. 2007), southern European cities (Alves et al. 2017), Athens (Andreou and Rapsomanikis 2009), and Italy (Belis et al. 2011). In recent years, research on $PM_{2.5}$ in China has been increasing (Li et al. 2015; Guo et al. 2003; Bandowe et al. 2014). Bandowe et al. (2014) tested the PAC concentration in $PM_{2.5}$ in Xi'an and explained that its changes were due to the urban environmental temperature, air pressure, wind speed, etc. Meanwhile, research shows that chemical substances in $PM_{2.5}$ in China are significantly higher than those in $PM_{2.5}$ in most Western countries, the chemical content is highest in winter, and the risk of cancer in winter is six times higher than that in summer. However, these studies all involve natural factors of $PM_{2.5}$ and ignore human factors. The impact of human social and economic activities on haze pollution cannot be ignored.

Smoggy weather occurs frequently, and although some natural factors cause smog, the most common cause of smog is that industrial production is extensive, the industrial structure is unreasonable, population growth is too fast, and the speed of economic development exceeds the carrying capacity of the environment. Zambrano-Monserrate et al. (2020) used the dynamic spatial Durbin model to explore the relationship and impact between GDP and ecology. Studying the relationship between the economy and environmental quality is a hot topic in environmental economics. Since the 1990s, Grossman and Krueger (1992) put forward the environmental Kuznets curve. They believe that an inverted U-shaped relationship exists between contaminants and economic income. With the continuous increase of income, the problem of pollution is increasingly serious. After reaching a turning point, pollution decreases with increasing income. The literature on EKC is increasingly rich. Some scholars have verified the relationship between economy and pollution. Hishan et al. (2019) selected data from sub-Saharan African countries and used generalized moment estimation analysis (GMM) to study the impact of urbanization on $PM_{2.5}$. The relationship between urbanization and $PM_{2.5}$ was an inverted U-shaped relationship. Some Chinese scholars have also verified this result (Dong et al. 2018; Zhao et al. 2018; Qi and Yan 2017). As research results become increasingly abundant, scholars have developed different views on EKC research due to the different objects and methods selected. U-shaped, inverted N-shaped, and N-shaped relationships have been found between the economy and the environment (He et al. 2016; Wang 2016; Wu et al. 2018). In addition, the most commonly used research methods are the IPAT model (Shang and Mao 2016) and the STIRPAT model (Wang et al. 2019; Guo and Ren 2018; Zhang and Han 2018).

Rapid population growth also places enormous pressure on the environment, which has aroused widespread concern about society. There is no consensus on the impact of population agglomeration on pollution. Some scholars believe that population agglomeration can improve haze pollution because population agglomeration can allow the sharing of resources, such as factories and roads, and avoid duplicate construction (Andreoni and Levinson 2001). The spatial structure of high-density cities reduces the use of private cars, increases the demand for public transportation, and reduces the carbon emissions of transportation (Brownstone and Golob 2008; Glaeser and Kahn 2009). In addition, population agglomeration has a scaling effect, which improves the utilization rate of public infrastructure and resources, thus improving the environment (Xiao and Shen 2019). Some scholars believe that population agglomeration aggravates pollution because a large number of people moving to cities and towns increases population density, leads to population urbanization, causes the consumption of extensive materials, causes more waste emissions, and leads to environmental pollution (Shao et al. 2016; Wang and Liu 2017).

With the deepening of research, the study of other social and economic factors that affect smog has gradually increased. Wang et al. (2018) found that the acceleration of the urbanization process increased haze pollution. Dong et al. (2018) selected an autoregressive distribution lag model to explore the impact of natural gas in Beijing on $PM_{2.5}$. They found that whether in the long or short term, the combustion of natural gas reduced $PM_{2.5}$, but the effect of the reduction gradually weakened over time. Xu and Lin (2016) used a time series to analyze the socioeconomic factors that affect smog, ignoring the characteristics of spatial diffusion and accumulation. Zhou et al. (2019) used data envelopment analysis (DEA) to study the human activity factors that affect $PM_{2.5}$. Guan et al. (2014) used an input-output model, taking the regional emission list as the input, and studied the factors that influence haze pollution through the structural decomposition method. The results of this method had hysteresis, and only specific factors were decomposed. These studies ignore the influence of natural factors, such as airflow, wind, and human factors. The diffusion characteristics of haze show that it is not mutually independent in space, so these traditional models cannot make accurate estimates of haze pollution. In view of the shortcomings of traditional research methods, a few scholars have started to use spatial metrology methods to study the causes and impact mechanisms of haze pollution (Li et al. 2019a; Luo and Li 2018; Anselin 1995).

In recent years, haze has attracted the attention of the Chinese government. China started to establish stations to monitor $PM_{2.5}$ in 2013. Therefore, $PM_{2.5}$ as an indicator of haze pollution is rarely studied, and the data available for analysis are limited. Most of the studies use data from recent years (He and Ma 2015; Liu and Du 2018). Pan et al. (2015) selected $PM_{2.5}$ data from October 2013 to September 2014 for their research. In terms of research scope, many projects study the overall haze situation in China, and the use of data is still at the provincial level (Shao et al. 2016; Kang 2016; Wu et al. 2018). Wu et al. (2018) used provincial data from China from 2000 to 2011 to explore $PM_{2.5}$. Some studies are limited to a few key cities or urban agglomerations (He and Ma 2015; Du et al. 2018; Liu and Pei 2017). Some scholars use cross-section data to study haze. Zhou et al. (2018) collected data from 945 sites in China in 2014, and Hao and Liu (2016) used data from 73 cities in China in 2013 to study factors affecting $PM_{2.5}$. The above literature greatly expands our research horizons but has some shortcomings, such as (1) the period of $PM_{2.5}$ is too short to reflect long-term trends in smog pollution. In the present article, the data span is 1998–2016, which avoids the shortcoming of studying too short a time period. (2) This present study studies data at the urban level, which provides a more focused view than using data at the provincial level and leads to more practical and instructive research conclusions. (3) Research in the existing literature focuses on national or local areas, and research combining national and local areas is relatively rare. First, this paper analyzes China as a whole and then divides China into three parts: the east, the middle, and the west. The conclusions of the present study are more pertinent and practical than those of previous studies. (4) Considering the characteristics of haze diffusion, the traditional model cannot make an accurate estimate. Therefore, the present study uses the spatial metrology method to study the characteristics of haze diffusion. Based on the abovementioned research, this article selects $PM_{2.5}$ as an indicator to measure smog and uses SDM to study the overall impact of economic development and population agglomeration on haze pollution in 287 urban panel datasets from 1998 to 2016 and then analyzes the three regions and puts forward corresponding policy recommendations.

Data

China's air pollution index did not include $PM_{2.5}$ in monitoring before 2012. The Chinese government issued the "Implementation Plan of the First Phase of the New Air Quality Standards" in 2012, which requires $PM_{2.5}$ monitoring in 74 cities across the country, and $PM_{2.5}$ officially became a monitoring index. Due to the short time of data acquisition in China, these data cannot reflect long-term trends in haze pollution, so this paper uses grid data obtained by the Battle Institute and the International Earth Science Information Network Center of Columbia University for analysis. On the basis of Van Donkelaar et al. (2015), grid data are converted from aerosol optical thickness (AOD) data. In this paper, ArcGis 10.0 is used to analyze grid data from 1998 to 2016 and convert them into $PM_{2.5}$ concentration values for 287 Chinese cities. Although China currently uses ground monitoring data, which are not easily affected by meteorological factors, China is large and the distribution of monitoring points is not dense, so ground monitoring based on points and areas cannot truly reflect more atmospheric conditions (Yu and Xiu 2018). Data obtained using satellites are non-point source data, which can comprehensively capture the characteristics of $PM_{2.5}$ concentration changes, making these data more realistic and accurate.

Spatial correlation analysis of haze

To study the spatial spillover effect of haze, this paper tests global and local autocorrelations.

Global spatial correlation test Based on the first law of geography,[1] this article uses global Moran's I to examine the characteristics of $PM_{2.5}$ and to further explore the spatial correlations of haze. The formula is:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \frac{1}{n}\sum_{i=1}^{n} x_i\right)\left(x_j - \frac{1}{n}\sum_{i=1}^{n} x_i\right)}{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \qquad (1)$$

where I is the global index of $PM_{2.5}$, n represents the number of cities, and W_{ij} represents the spatial weight matrix. x_i and x_j represent haze observation values of city i and city j, respectively. When the value range of I is [− 1.0) and it is infinitely close to − 1, $PM_{2.5}$ shows a negative correlation in space; when the value range is (0,1] and I is infinitely close to 1, $PM_{2.5}$ shows a positive correlation in space; and when I is infinitely close to 0, the $PM_{2.5}$ has no correlation in space. In the selection of the spatial weight matrix, most scholars use the 0–1 adjacency matrix. If there is a common edge or point in the two areas, they are adjacent and the value is 1; otherwise, it is 0 (Liu and Jiang 2017; Ma and Zhang 2014). However, there will be a city that is not adjacent to any other city, causing deviations in the results.

When introducing a spatial econometric model, we must construct the spatial weight matrix. The 0–1 matrix is commonly used. However, this paper uses data from 287 cities, and the problem of independent cities affects the accuracy of the data. This paper uses the commonly used inverse distance matrix and economic geographical distance matrix, which not only consider the spatial impact of geographical distance but also reflect the fact that economic factors have regional spillover and radiation effects that can reflect the spatial correlation degree of cross-section units more comprehensively and objectively. On the other hand, these matrixes can test the stability of the model.

This paper draws on the perspective of Luo and Li (2018) and uses the inverse distance spatial weight matrix (W_1). The basic idea of W_1 is that as the distance increases, the spatial correlation of haze will gradually weaken. The formula is:

$$w_{1,ij} = \begin{cases} 1/d_{ij} & i \neq j \\ 0 & i = j \end{cases} \qquad (2)$$

where W_1 refers to the reciprocal of the nearest distance between area i and area j. This matrix can not only reflect the degree of adjacency of two regions but can also reflect the traffic convenience between two regions.

The second matrix is the economic-geographic distance weight matrix (W_2), which is the product of the reciprocal of the absolute value of the difference between the per capita GDP of regions i and j and the reciprocal of the nearest distance between regions i and j. The formula is:

$$w_{2,ij} = \begin{cases} \frac{1}{d_{ij}} * \frac{1}{\left|\overline{Y_i} - \overline{Y_j}\right|} & i \neq j \\ 0 & i = j \end{cases} \qquad (3)$$

where $\overline{Y_i} = \sum_{t=T_0}^{T} Y_{it}/(T - T_0)$ and Y_{ij} is the per capita GDP of city i in year j. This weight considers the spatial impact of geographical distance and also reflects the spillover and diffusion effects of economic factors, which can more comprehensively reflect the spatial correlation.

According to Table 1, under the two spatial weight matrices, W_1 and W_2, Moran's I of $PM_{2.5}$ passes the test at the level of 5%, and the value of the coefficient is greater than 0, indicating that $PM_{2.5}$ has a spatial spillover and haze pollution has diffusion and agglomeration.

Local spatial correlation test Although the global test reflects the overall correlation of variables in space, it also ignores the

[1] The first law of geography: everything is related, the closer things are, the more closely they are related.

Table 1 Global Moran index table of smog pollution from 1998 to 2016

	W_1		W_2	
Year	I	P value	I	P value
1998	0.156	0.000	0.068	0.011
1999	0.168	0.000	0.106	0.000
2000	0.178	0.000	0.094	0.001
2001	0.186	0.000	0.098	0.001
2002	0.187	0.000	0.116	0.000
2003	0.204	0.000	0.150	0.000
2004	0.183	0.000	0.118	0.000
2005	0.181	0.000	0.111	0.000
2006	0.179	0.000	0.127	0.000
2007	0.197	0.000	0.136	0.000
2008	0.190	0.000	0.139	0.000
2009	0.180	0.000	0.132	0.000
2010	0.183	0.000	0.123	0.000
2011	0.188	0.000	0.124	0.000
2012	0.186	0.000	0.137	0.000
2013	0.187	0.000	0.120	0.000
2014	0.184	0.000	0.133	0.000
2015	0.227	0.000	0.173	0.000
2016	0.215	0.000	0.159	0.000

characteristics of local areas. To analyze the regional characteristics of haze more carefully, this paper introduces the local spatial correlation index (LISA) for further research. The formula is:

$$I_i = \frac{\left(x_i - \frac{1}{n}\sum_{i=1}^{n} x_i\right)}{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2} \sum_{i=1}^{n} W_{ij}\left(x_j - \frac{1}{n}\sum_{i=1}^{n} x_i\right) \tag{4}$$

where I_i is the correlation degree of $PM_{2.5}$ between region i and neighboring regions. The other variable settings are the same as those for the global test. When the value range of I is (0,1], it means that a high $PM_{2.5}$ concentration is surrounded by a high $PM_{2.5}$ concentration or a low haze concentration is surrounded by a low haze concentration, and $PM_{2.5}$ shows a H-H or L-L concentration; when the value range of I is [− 1,0), that area i has a negative correlation with the surrounding area; that is, a low $PM_{2.5}$ concentration is surrounded by a high $PM_{2.5}$ concentration or a high haze concentration is surrounded by a low haze concentration, and $PM_{2.5}$ shows a L-H or H-L concentration.

To further study the spatial distribution characteristics of haze pollution, Stata 14.0 is used to calculate the local Moran index value of Chinese $PM_{2.5}$ from 1998 to 2016, and a scatter map of the corresponding year is drawn. Taking the data from the inverse distance matrix (W_1) as a representative, this paper selects the Moran scatter diagram from 1998, 2004, 2010, and 2016 (Fig. 1).

In Fig. 1, the scatter diagram is divided into four quadrants. The first quadrant is an H-H concentration area, that is, an area where a high haze area is adjacent to another high haze area; the third quadrant is an L-L concentration area; i.e., a low haze area is adjacent to another low haze area. The second quadrant is a low-high clustering region, and the fourth quadrant is a high-low clustering region. On the whole, the local Moran index of $PM_{2.5}$ over 4 years is greater than 0, and most samples are in the first and third quadrants, which reflects a positive correlation, indicating that smog has a spatial correlation.

This paper uses ArcGis 10.0 to plot the distribution of $PM_{2.5}$ over 4 years. $PM_{2.5}$ is divided into five grades: excellent (0~15 μg/m^3), good (15~30 μg/m^3), light (30~45 μg/m^3), medium (45~60 μg/m^3), and heavy pollution (> 60 μg/m^3), which are shown in Fig. 2. It can be seen from the figure that there is a clustering phenomenon of haze pollution. Low haze pollution and surrounding areas are clustered, especially in the western region. High haze pollution areas are also clustered. In addition, haze pollution shows an increasingly serious trend over time. In the chart for 2010 to 2016, the concentration of $PM_{2.5}$ has a downward trend.

Theoretical mechanism, model construction, and empirical research

Theoretical mechanism

Effect of economic development on haze pollution The relationship between the environment and the economy has always been a hot topic in academic circles. Given the increasingly serious haze pollution in China, scholars began to explore the relationship between haze pollution and economic development. In an exploration of the causes of haze pollution, the influencing factors of haze pollution were determined, and corresponding haze control policies were implemented to not only improve the atmospheric environment but also ensure human health. Given China's reform and opening-up, the country's comprehensive national strength has been continuously enhanced, and the degree of opening to the outside world has gradually strengthened. Simultaneously, inexpensive labor has attracted many foreign enterprises to invest. To protect their environment, enterprises in developed countries transfer some industries with high pollution and high energy consumption to China, which puts pressure on China's environment (Shahbaz et al. 2015). In addition, the improvement in China's degree of opening-up has brought new energy technologies, which has produced technological effects and has improved the country's haze situation (Zhang et al. 2019). During the critical period of economic

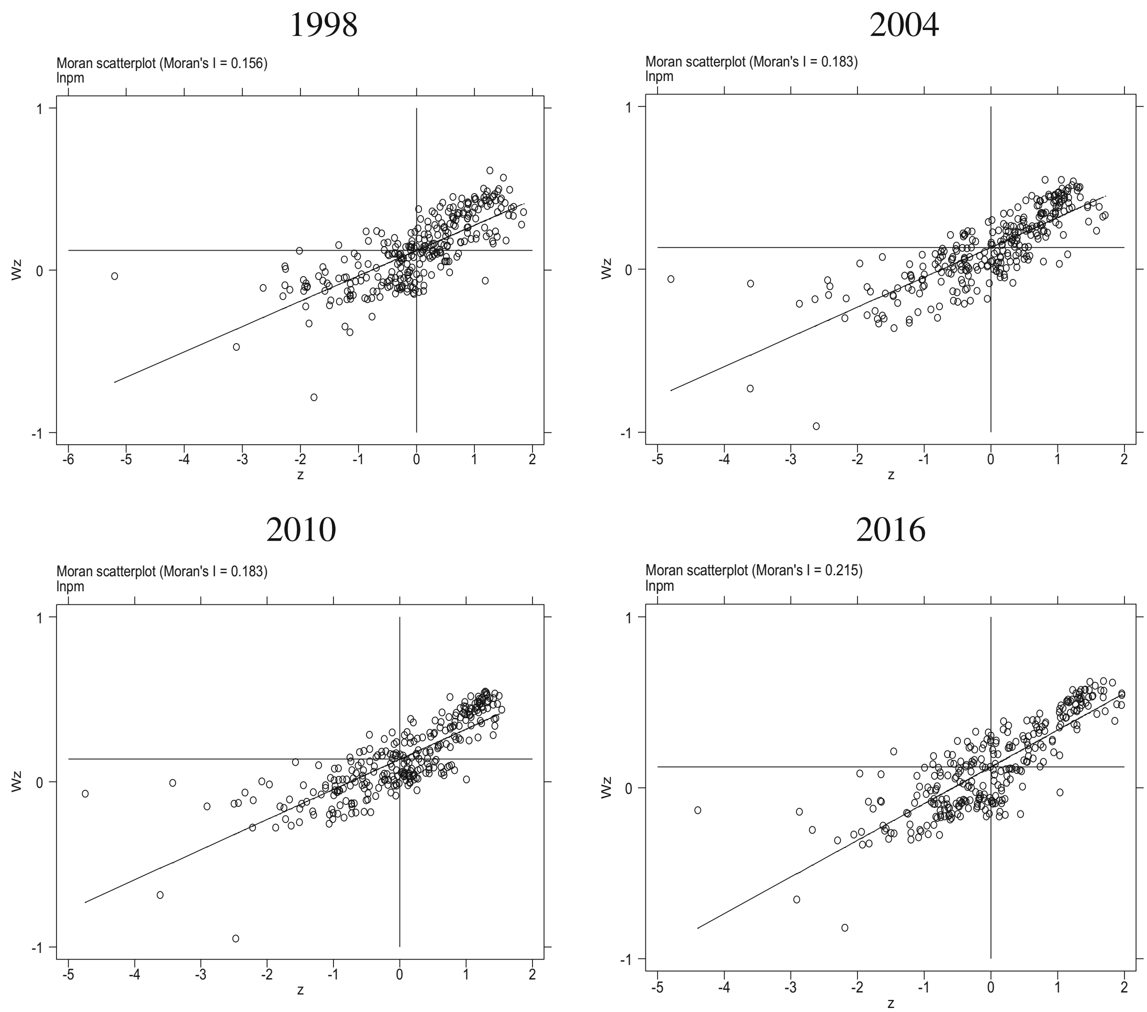

Fig. 1 Moran scatter plot of haze pollution in Chinese cities

transformation, the development of the economy also promotes continuous optimization and upgrades to industrial structures. The continuous expansion of market scale and the increasing diversity of the public's demands have increased their demand for low pollution products with environmental protection awareness under the condition of meeting basic material conditions. Therefore, the proportion of the tertiary industry dominated by the service industry is increasing, and the manufacturing industry with its high energy consumption and high pollution is being reformed to improve production capacity and reduce haze pollution.

Given the development of the economy and the progress of science, China has realized the importance of innovation. The government has been increasing its innovation efforts, encouraging enterprises to develop new energy and green environmental protection technologies, optimizing traditional high-pollution industries, and improving the use efficiency of resources and energy to improve the environment and develop technical effects. However, the progress of technology also increases the demand for energy, which leads to a stronger pollution and energy rebound effect (Shao et al. 2019). Because China has a large population base and increasing population density, the country consumes significant energy and resources, and the emission of pollutants is also increasing. Population increases cause housing demand to increase, which drives the construction of real estate and produces significant dust. At the same time, population increases also lead to demand for automobiles, which produces a large volume of vehicle exhaust emissions that aggravates haze pollution and produces the population scale effect (Zhao et al. 2019; Tong and Wang 2014). Since the reform and opening-up, urbanization has become a new driving force for China's economic development. The inevitable result of economic and social development is an important sign for a country or region to engage in modernization. The construction of new urbanization structures should adhere to green development, change the traditional production and lifestyle, eliminate backward industries, accelerate the construction of new industries, and promote industrial innovation and upgrading to improve the quality of haze pollution (Liu and Xu 2017).

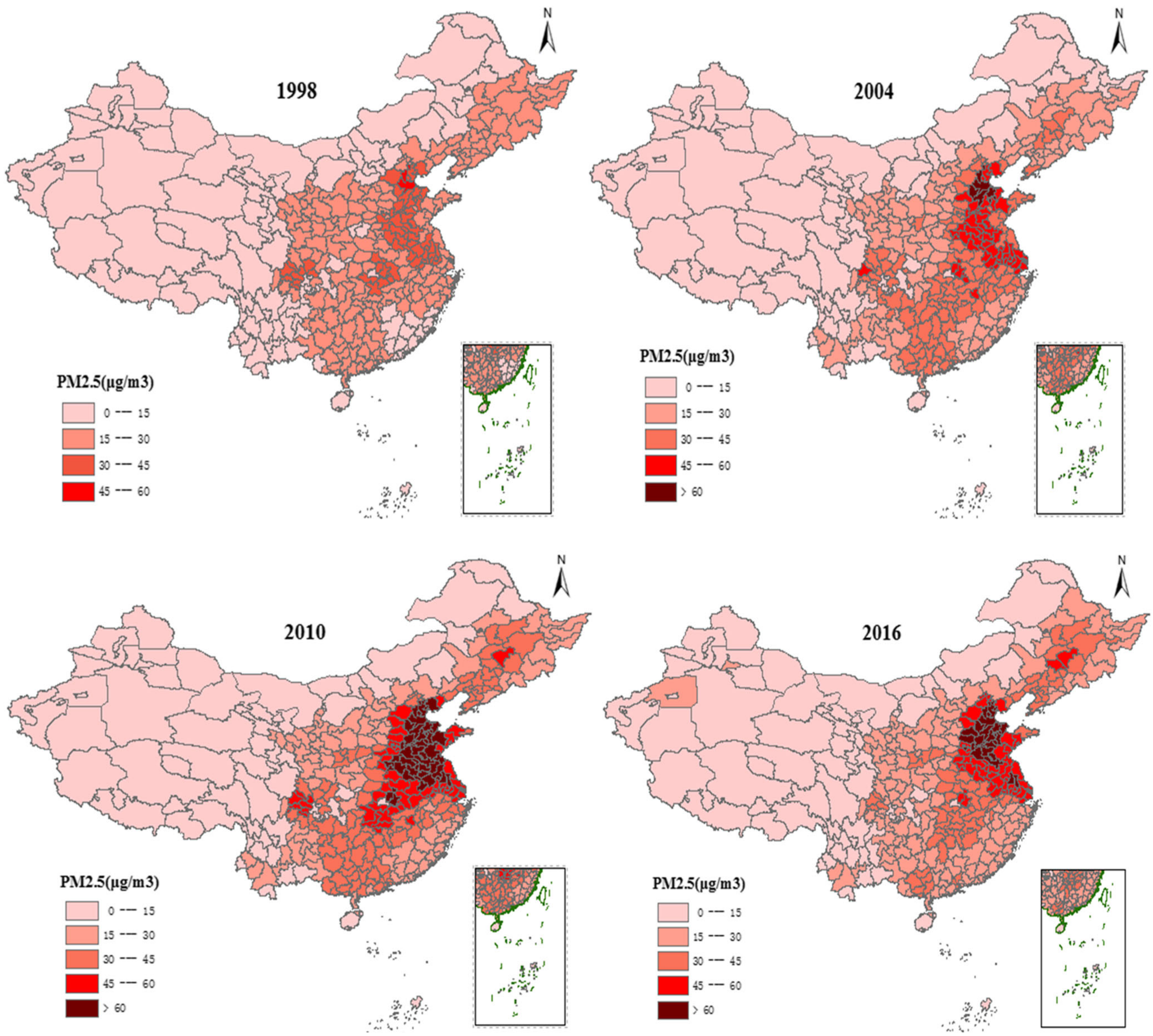

Fig. 2 National distribution of the $PM_{2.5}$ concentration (In order to show the change of the $PM_{2.5}$ concentration in China from 1998 to 2016, we developed a website http://www.aqipm.top/, which can be accessed for details)

Variable selection and source

In the 1970s, Holdren and Ehrlich (1974) proposed the IPAT model to study the impact of wealth, population size, and technological level on the ecological environment. However, the model ignored the application limitations of multiple factors that affect the environment. York et al. (2002) redefined the IPAT model and expressed it in a random form. The STIRPAT model was established and improved in this paper, and its variables are selected based on the STIRPAT model.

Explained variable Haze pollution (ln*PM*): $PM_{2.5}$ is the primary particle in haze, which can easily cause respiratory diseases. High concentrations of $PM_{2.5}$ can cause death and seriously endanger human health. Therefore, the $PM_{2.5}$ concentration is used to express the degree of haze pollution in this paper, and the data come from the $PM_{2.5}$ concentration value parsed from grid data.

Core explanatory variables This article uses the actual GDP to represent the level of economic development (ln*GDP*). This paper takes 2000 as the base period and adjusts the nominal GDP of each city to its real GDP through a deflator. Population agglomeration (ln*P*) is represented by population density (Liu et al. 2019; Luo and Li 2018). At present, scholars have not reached a consistent conclusion about the influence of population agglomeration on smog pollution.

Control variables Industrial structure (ln*TI*): with the development of the economy and science, the industrial structure continues to be optimized and upgraded, and the proportion of tertiary industries with low pollution levels is constantly increasing. Therefore, this paper chooses the proportion of tertiary industries in GDP to represent the industrial structure (Chen 2016). In the existing literature, urbanization (ln*AE*) is usually measured by the percentage of permanent residents in the total population. However, due to the long time period and large number of cities studied, our data access is limited. Therefore, we select the average number of on-the-job employees to represent ln*TI* (Song 2000). Technical level (ln*S*): the fundamental driving force of technological progress is science and technology. The expenditure on science in the public finance of each city is used to express the technical level (Dong 2016). At present, scholars have different views on the impact of opening to the outside world (ln*FDI*) on haze pollution. There is no consensus on whether opening to the outside world improves or intensifies haze pollution. This paper uses the actual amount of foreign capital used in a year to express this index (Liu et al. 2019; Shao et al. 2016).

Market scale (ln*M*): the continuous expansion of the market scale leads to economic agglomeration and can be used to further explore the impact of the economy on haze pollution. This paper uses total retail sales of social consumer goods to measure the market scale (Luo and Li 2018). Transportation intensity (*T*): convenient transportation is conducive to exchanges with the regional external economy, attracts investment, and improves the economic level. In addition, emissions of automobile exhaust aggravate haze pollution. To explore the impact of this factor, this paper uses the per capita urban road area to measure emissions of automobile exhaust (Liu et al. 2019; Shao et al. 2016). Material capital (ln*K*): Zivin and Neidell (2012) believe that the combination of material capital and labor can improve production efficiency, thus affecting economic development. The indicators are measured by fixed-asset investments. The details are shown in Table 2.

The data come from the "China City Statistical Yearbook". To ensure the authenticity, integrity, and continuity of the data, 287 cities from 1998 to 2016 were ultimately selected. The logarithm of the relevant variables was taken to reduce errors.

Model selection and construction

Based on EKC, this paper introduces the quadratic term of real GDP into the model using the method of Ma et al. (2016b). Three commonly used spatial econometric methods are used. The spatial lag model (SLM) is mainly used to study the spatial spillover effect of this region on other regions. In the spatial error model (SEM), the influence of spatial factors on the error term becomes complex and can no longer be simply subjected to a normal distribution. The error term may contain other factors affecting haze pollution, which causes a strong correlation; therefore, a spatial error model is constructed. The spatial Durbin model (SDM) contains spatial lag factors of the explanatory variables. This model can better solve the problem of variable omission than the SEM and the SLM and ensures an unbiased estimation of coefficients.

As for the selection of models, the LR test can be performed according to the judgment criteria proposed by LeSage and Pace (2009). The test has two hypotheses: $H_0: \theta = 0$ and $H_0: \theta + \rho\beta = 0$. The first hypothesis tests whether the SDM degenerates into the SLM, and the second hypothesis is used to test whether the SDM degenerates into the SEM. If both hypotheses are rejected, the SDM is optimal; otherwise, the SLM or the SEM should be selected. It can be seen that the spatial Durbin model is more general.

Spatial model selection First, we can further judge whether the spatial panel model should be used through the LM test and diagnose the four statistics of the traditional OLS model. If all the OLS models are rejected by the four statistics, we cannot directly judge whether the spatial lag or spatial error model should be used. We should also judge the three spatial models through the WALD and LR tests.

The results presented in Table 3 show that the four statistics of traditional OLS reject the original hypothesis. It is further

Table 2 Economic indicators and sources of haze pollution

Influencing factor	Index	Variable
Economic development level	Real GDP	ln*GDP*
Population agglomeration	Population density	ln*P*
Industrial structure	Proportion of tertiary industry in GDP	ln*TI*
Urbanization	Average number of employees	ln*AE*
Technical level	Technology expenditure	ln*S*
Opening to the outside world	Actual foreign capital used in the year	ln*FDI*
Market scale	Total retail sales of consumer goods	ln*M*
Traffic factors	Per capita urban road area	*T*
Material capital	Investment in fixed assets	ln*K*

Table 3 Diagnostic results of the spatial model

	W_1		W_2		
Test statistic	χ^2	P	χ^2	P	
LM_lag	3559.0749***	0.000	1024.6510***	0.000	
LM_Error	25,062.6014***	0.000	1302.2290***	0.000	
Robust LM_lag	189.2469***	0.000	106.2542***	0.000	
Robust LM_Error	21,692.7735***	0.000	383.8322***	0.000	
spatial-fixed effect LR_test	263.3163 (0.8387)		time-fixed effect LR_test	1427.4983*** (0.000)	
Wald_lag	152.8206***	0.000	Wald_Error	114.6201***	0.000
LR_lag	149.0360***	0.000	LR_Error	111.9864***	0.000

confirmed that smog pollution has a spatial spillover effect. From the results of the WALD and LR tests, the estimates reject the original hypothesis. Therefore, the spatial Durbin model (SDM) is more suitable for this research. Based on the results of the Hausman test and the LR test, this article finally chooses the time-fixed effect of the SDM for empirical study.

Model construction Through this spatial correlation test, haze is observed to be not independent in each region. In the traditional OLS model, the variables are independent of each other. Therefore, the traditional OLS model is no longer applicable to this paper. This paper attempts to use spatial econometric models to study whether the economy of each city affects smog in neighboring areas. To comprehensively and carefully study the long-term relationship between the economy and $PM_{2.5}$, according to the results of the model's test, this paper selects the SDM for the empirical research. The model is as follows:

$$\begin{aligned}\ln PM_{it} = \beta_0 + \rho \times W\ln PM + \beta_1 \times \ln GDP + \beta_2 \times (\ln GDP)^2 + \beta_3 \times \ln P + \beta_4 \times \ln AE \\ + \beta_5 \times \ln S + \beta\times_6 \ln FDI + \beta_7 \times \ln M + \beta_8 \times \ln T + \beta_9 \times \ln TI + \beta_{10} \times \ln K + \theta_1 \\ \times W\ln GDP + \theta_2 \times W(\ln GDP)^2 + \theta_3 \times W\ln P + \theta_4 \times W\ln AE + \theta_5 \times W\ln S \\ + \theta\times_6 W\ln FDI + \theta_7 \times W\ln M + \theta_8 \times W\ln T + \theta_9 \times W\ln TI + \\ \theta_{10} \times W\ln K + \delta_i + \mu_i + \varepsilon_{it} \\ \varepsilon_{it} \sim N(0, \sigma_{it}^2 I_n)\end{aligned} \quad (5)$$

In the above model, δ_i is the spatial effect and μ_t is the temporal effect.

Results analysis

The empirical results are shown in Table 4. Under the two spatial weight matrices, the two indicators of the economic development level pass the significance test. The primary term of the coefficient is negative, and the secondary term is positive. It can be seen that China's haze pollution conforms to the EKC, which is an inverted U-shaped relationship. It is consistent with the research results of Liu et al. (2019). During the initial economic development stage, industrialization develops rapidly, pollutant emissions exceed the standard, urban buildings lead to increases in dust, and haze pollution continues to aggravate. When reaching a turning point, with the improvement of the economic level, the haze pollution situation improves. The reason for this phenomenon is that the harm caused by haze attracts the attention of all sectors of society and attention is paid to environmental protection while developing the economy. The product of the economy and the matrix is tested at the level of 5% in W_2, which shows that the economic development of neighboring areas has a

Table 4 Spatial metrology model results

	W_1		W_2	
Variable	Coefficient	P	Coefficient	P
ln*GDP*	0.283**	0.015	0.993***	0.000
ln*GDP2*	− 0.007*	0.085	− 0.032***	0.000
ln*P*	0.321***	0.000	0.391***	0.000
ln*S*	− 0.039***	0.000	− 0.032***	0.000
ln*AE*	− 0.040***	0.003	− 0.009	0.531
ln*FDI*	− 0.007*	0.052	0.011***	0.003
ln*TI*	− 0.181***	0.000	− 0.251***	0.000
ln*K*	0.052***	0.000	0.105***	0.000
ln*M*	− 0.031**	0.014	− 0.042***	0.003
T	0.000	0.687	− 0.002***	0.000
*W**ln*GDP*	− 0.186	0.853	0.805**	0.032
*W**ln*GDP2*	− 0.015	0.655	− 0.028**	0.024
*W**ln*P*	0.064	0.113	− 0.084***	0.000
*W**ln*S*	− 0.385***	0.000	0.002	0.912
*W**ln*AE*	1.227***	0.000	0.041	0.216
*W**ln*FDI*	0.062**	0.031	− 0.029***	0.002
*W**ln*TI*	− 0.183	0.300	0.387***	0.000
*W**ln*K*	0.183***	0.007	− 0.009	0.748
*W**ln*M*	0.143	0.382	− 0.097**	0.025
*W***T*	− 0.015***	0.000	− 0.003**	0.015
ρ	0.951***	0.000	0.354***	0.000
R^2	0.025		0.459	

spillover effect on haze pollution in the local area, and the relationship between them is also an inverted U shape. With the continuous increase of per capita income in neighboring areas, the concentration of $PM_{2.5}$ in local area increases first and then decreases.

Under two spatial weight matrices, the coefficient of population agglomeration (ln*P*) is significantly positive. The value of population agglomeration is the largest of all the influencing factors; Liu et al. (2020) also considered that population agglomeration is the decisive human factor affecting haze pollution, which indicates that it is the primary factor affecting haze pollution. Population agglomeration has a certain incremental effect on the emission of haze pollution; that is, population agglomeration increases infrastructure construction, consumption, and industrial output as well as energy and resource consumption and pollution emissions increase haze pollution. Under the W_2 weight matrix, W*ln*P* is significantly negative, showing that the increase of the population density and the flow of people in neighboring areas alleviate haze in this area, reflecting the siphoning effect of one region on its surrounding areas.

The influencing factor of the technical level (ln*S*) passes the significance test in W_1 and W_2, the continuous progress of the technology level can improve haze pollution (Sun et al. 2019; Dong 2016), and the coefficient of W*ln*S* on adjacent areas is also negative in W_1, which shows that the continuous progress of the technical level can improve smog in surrounding areas. Given the development of the economy, the government has increased its innovation efforts and increased investments in scientific and technological research, which provides strong support for enterprises, encourages enterprises to develop new energy technologies, develops green environmental protection technologies, eliminates backward high pollution and high energy consumption technologies, and optimizes traditional technologies, such as reducing the use efficiency of coal and other resources through technical optimization. The coefficient of urbanization (ln*AE*) is negative in W_1. The acceleration of urbanization has improved haze pollution. When the urbanization level is increased by 1%, haze pollution is improved by 4%. This is because great changes have occurred in the development of urbanization, and the development of the non-agricultural industry has led to the vigorous development of a low pollution service industry. In the process of vigorously developing urbanization, the government has paid increasing attention to the construction of ecological civilization, emphasizing energy conservation in the development mode, reducing the harm to nature, and promoting green travel lifestyle and urban construction modes.

The coefficients of ln*FDI* under the two spatial matrices are different. Under the W_1 weight matrix, the coefficient is small; therefore, this paper analyzes the significance of the results in W_2. The coefficient of openness to the outside world (ln*FDI*) is significantly positive and has passed the significance test at the 1% level, which shows that FDI aggravates haze pollution (Shahbaz et al. 2015; List and Co 2000; Ren et al. 2014). To obtain low-cost labor, developed countries transfer highly polluting industries to the region, resulting in the deterioration of the local environment. The coefficient of the opening-up level and matrix product (W*ln*FDI*) is significantly negative. FDI in neighboring regions reduces haze pollution in the region (Zhang and Zhou 2016; Dong et al. 2012). The reason for this phenomenon is that the region learns to introduce green advanced energy technologies from foreign-funded enterprises in neighboring regions to improve the region's environment.

The influencing factor of the industrial structure (ln*TI*) is negative, showing that the increase of the tertiary industry improves haze pollution (Dong et al. 2019), because tertiary industry is mostly composed of low-energy green industries, which have little impact on the environment. In addition, heavy industry, which causes serious pollution, has been gradually rectified or transferred to neighboring areas, resulting in the aggravation of haze pollution in neighboring areas. The coefficient of W*ln*TI* in W_2 is positive, indicating that the optimization and upgrading of the industrial structure in neighboring areas aggravate local haze pollution.

The coefficient of material capital (ln*K*) is positive. Although China's fixed-asset investment is increasing, the proportion of investment in green industry is still low, which increases the burden of the environment in the region. Under the W_1 weight matrix, W*ln*K* is significantly positive, meaning that the increase of fixed-asset investments in neighboring areas also aggravates haze pollution in the local area. The coefficients of the market scale (ln*M*) and traffic factor (*T*) are negative, indicating that the economic agglomeration brought by the market scale and convenient transportation can improve smog pollution.

Analysis of the spatial spillover results

A general panel model studies independent variables and dependent variables without considering spatial factors. However, when considering spatial factors, the problem becomes more complex because the change of a certain factor can not only cause a change in haze pollution in this area but may also affect haze in adjacent areas. Lesage and Pace (2009) put forward three kinds of spatial effects: direct, indirect, and total effects. The direct effect indicates the average degree of influence of the independent variable on haze in the local area. The indirect effect refers to the influence of a given factor on smog in adjacent areas. The total effect is the impact of the explanatory variable on haze in all areas.

The basic form of the spatial Durbin model: $y = \rho Wy + \alpha\tau_n + X\beta + WX\gamma + \varepsilon$

Transform the formula: $(I_n-\rho W)y=\alpha\tau_n+X\beta+WX\gamma+\varepsilon$

$$y=\sum_{r=1}^{k}S_r(W)x_r+V(W)\alpha\tau_n+V(W)\varepsilon \quad (6)$$

where:

$$S_r(W)=V(W)\left(I_n\beta_\gamma+W\theta_r\right)$$
$$V(W)=(I_n-\rho W)^{-1}=I_n+\rho W+\rho^2W^2+\rho^3W^3+\cdots$$

Expand formula (6):

$$\begin{bmatrix}y_1\\y_2\\\vdots\\y_n\end{bmatrix}=\sum_{r=1}^{k}\begin{bmatrix}S_r(W)_{11} & S_r(W)_{12} & \cdots & S_r(W)_{1n}\\S_r(W)_{21} & S_r(W)_{22} & \cdots & S_r(W)_{2n}\\\cdots & \cdots & \cdots & \cdots\\S_r(W)_{n1} & S_r(W)_{n2} & \cdots & S_r(W)_{nn}\end{bmatrix}\begin{bmatrix}x_{1r}\\x_{2r}\\\vdots\\x_{nr}\end{bmatrix}+V(W)\alpha\tau_n+V(W)\varepsilon$$

The partial derivative of y_i to x_{ir} is $\frac{\partial y_i}{\partial x_{ir}}=S_r(W)$, which represents the direct effect. This derivative is obtained by calculating the mean value of the diagonal of the matrix $S_r(W)$. The partial derivative of y_i to x_{jr} is $\frac{\partial y_i}{\partial x_{jr}}=S_r(W)$, which represents the indirect effect in space. This derivative is obtained by calculating the average value of the elements on the non-diagonal of the matrix $S_r(W)$. The total effect is the sum of the direct effect and the indirect effect, which is obtained from the average value of many elements in the matrix $S_r(W)$.

Compared with the two matrices presented in Table 5, the results in W_2 pass the significance test. Therefore, this paper mainly analyzes the results of W_2. From these results, we can see that the direct effects are consistent with the signs of the independent variables in the spatial Durbin model. The coefficients of the primary and secondary terms of economic development in the indirect effects are 1.697 and −0.058, respectively. The influence of the regional economy on neighboring areas also has an inverted U-shaped relationship, so in general, China's economy conforms to the EKC hypothesis. For the indirect effect, the population size (ln*P*) coefficient is positive and has passed the significance test at the 1% level. This coefficient shows that population agglomeration also has adverse effects on the environment of neighboring areas. The reason may be that population agglomeration makes urban buildings expand continuously, putting land and other resources in short supply. Moreover, automobile exhaust emissions increase and dust and other particles increase, worsening and expanding haze in the region. From the overall effect, population factors still affect the primary factor of haze pollution.

The coefficient of ln*TI* on neighboring areas is positive, and through a significance test at the 1% level, every increase in the proportion of the tertiary industry aggravates haze in neighboring areas by 0.440. Because of upgrades to the industrial structure in this region, extensive industries are transferred to neighboring areas under strict control, which causes smog pollution in neighboring regions to continue to rise. The positive impact of industrial structure on adjacent regions is greater, making the overall effect positive, and the industrial structure is positive for haze pollution. The indirect effect coefficient of ln*FDI* is significantly negative and has passed the significance test, which shows that FDI in this region can reduce haze in neighboring areas. This is because local governments share the experience of foreign advanced technology, green energy technology, and environmental pollution reduction to surrounding areas to reduce haze pollution. From the overall effect, FDI can reduce haze pollution. The indirect effect coefficient of ln*S* is negative, but the result is not significant. From the total effect, the coefficient of the technology level is significantly negative, which indicates that environmental quality has improved from the continuous improvement in technology. Both the indirect effect coefficients of market size (ln*M*) and traffic intensity (*T*) are negative. For each additional unit of variables, market size and traffic

Table 5 Space spillover results

Variable	W_1 Direct	W_1 Indirect	W_1 Total	W_2 Direct	W_2 Indirect	W_2 Total
ln*GDP*	0.290*	0.777	1.067	1.059***	1.697***	2.756***
ln*GDP2*	−0.009*	−0.424	−0.433	−0.034***	−0.058***	−0.091***
ln*P*	0.350***	7.864***	8.214***	0.394***	0.081***	0.475***
ln*S*	−0.072***	−8.890***	−8.962***	−0.033***	−0.014	−0.047**
ln*AE*	0.052*	25.039***	25.090***	−0.007	0.055	0.048
ln*FDI*	−0.003	1.157	1.154	0.010***	−0.0338***	−0.028*
ln*TI*	−0.208***	−7.905	−8.113	−0.233***	0.440***	0.208**
ln*K*	0.070***	4.843**	4.913**	0.106***	0.039	0.145***
ln*M*	−0.022	2.425	2.404	−0.048***	−0.168**	−0.216***
T	−0.001*	−0.327***	−0.328***	−0.002***	−0.005***	−0.007***

intensity improve haze pollution by 0.168 and 0.005, respectively. From the total effect, the continuous expansion of market scale and the improvement in traffic convenience can reduce haze pollution.

Study on the subregion of haze pollution

To further investigate the influences of economic development and population agglomeration on haze pollution, we divided the 287 cities into east, central, and west regions. Due to the difficulty of data acquisition, 31 provinces except Hong Kong, Macao, Taiwan, and Nansha Islands are taken as the study area, and their distribution is shown in Fig. 3.

In the eastern and central parts of China, the Moran's *I* values of $PM_{2.5}$ are all significantly positive. The Moran index of most years is positive and passed the significance test in the west, except that a few years that it did not pass the significance test. Therefore, there is a significant spatial correlation among the three regions of China (Table 6).

In this paper, we use the time-fixed effect of the SDM to analyze the results of the three regions. The primary coefficients of the economy are all positive and the secondary coefficients are all negative in the three regions, but the coefficients only pass the significance test in the eastern and central regions. The relationship between real GDP and haze is an

Table 6 Spatial correlation test results based on region

	East		Middle		West	
Year	*I*	*P* value	*I*	*P* value	*I*	*P* value
1998	0.356	0.000	0.143	0.002	0.093	0.075
1999	0.324	0.000	0.196	0.000	0.206	0.002
2000	0.363	0.000	0.125	0.006	− 0.001	0.420
2001	0.387	0.000	0.188	0.001	0.025	0.290
2002	0.393	0.000	0.171	0.000	0.055	0.174
2003	0.436	0.000	0.146	0.002	0.116	0.040
2004	0.328	0.000	0.208	0.000	0.077	0.106
2005	0.341	0.000	0.191	0.000	0.087	0.086
2006	0.332	0.000	0.184	0.000	0.140	0.019
2007	0.345	0.000	0.209	0.000	0.053	0.181
2008	0.334	0.000	0.194	0.000	0.074	0.116
2009	0.308	0.000	0.156	0.001	0.105	0.052
2010	0.355	0.000	0.143	0.002	0.170	0.007
2011	0.330	0.000	0.168	0.000	0.140	0.019
2012	0.328	0.000	0.197	0.000	0.158	0.011
2013	0.355	0.000	0.142	0.002	0.102	0.056
2014	0.328	0.000	0.166	0.000	0.098	0.064
2015	0.353	0.000	0.118	0.008	0.101	0.060
2016	0.358	0.000	0.092	0.028	0.079	0.104

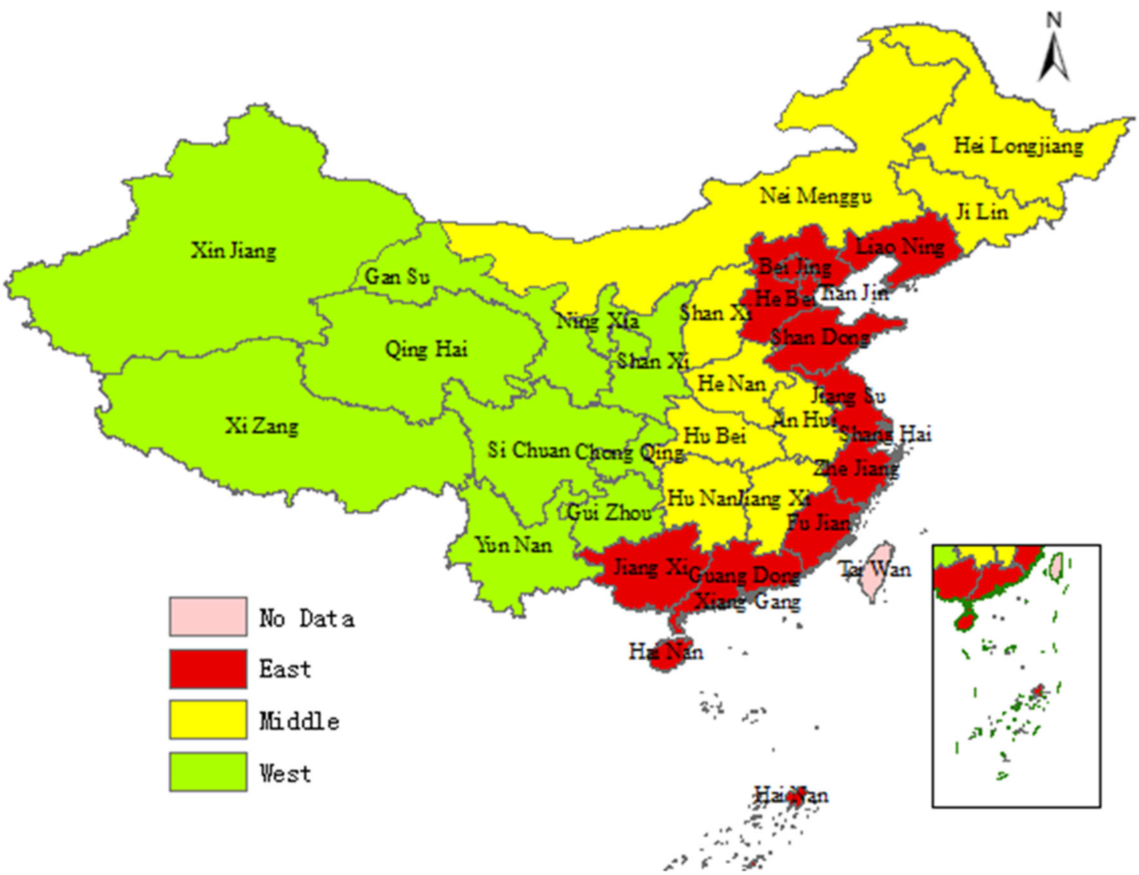

Fig. 3 Geographical distribution of the eastern, central, and western regions

inverted U-shaped curve, which is consistent with the overall situation of the country. However, the impact of income on haze in neighboring areas is not the same. The eastern area has a U-shaped relationship, while the central and western areas have an inverted U-shaped relationship. The coefficients of population agglomeration are positive in all three regions. Among all the positive factors, the ln*P* value of the three regions is the largest, indicating that the population concentration is the primary factor that aggravates haze pollution. In the eastern region, the coefficient value of the product of the spatial weight matrix and population density (*W**ln*P*) is significantly positive, and population aggregation in neighboring areas aggravates haze in the region. In the central region, the coefficient value of *W**ln*P* is significantly negative. The population concentration in neighboring areas reduces haze in this region, whereas the coefficient value in the western region is not significant (Table 7).

All of the industrial structure and technical level coefficients of the three regions are all negative and pass the significance test, which shows that the increasing output value of the tertiary industry and the continuous progress of technology can improve haze pollution, which is consistent with the overall situation of the entire country. The coefficient of the product of industrial structure and the spatial weight matrix (*W**ln*TI*) in central and western regions is positive, and the optimization and upgrading of the industrial structure in neighboring regions bring pressure on the local environment. The urbanization (ln*AE*) coefficient of eastern and western regions is positive and passes the significance test at the 1% level. In the early stage of urbanization, the eastern region only pays attention to development and ignores damage to the environment; haze pollution increased by 0.070 per unit of urbanization level. In the western region, because of its underdeveloped economy, backward technology, and low level of urbanization, haze pollution is aggravated. The urbanization coefficient is negative, which indicates that urbanization improves haze pollution in the central region. The coefficient of *W**ln*AE* in eastern and central regions is significantly positive, and the acceleration of the urbanization process in adjacent areas aggravates haze pollution in the region. Except for the central region, the coefficients of ln*FDI* are negative, which indicates that FDI improves haze pollution by introducing foreign advanced technology, while FDI in the central region intensifies pollution. In the eastern and western regions, haze pollution in the neighboring areas can be improved by 0.095 and 0.028 for each unit of the opening-up level. The material capital coefficient of all three regions is positive. Increasing population causes labor-intensive

Table 7 Test results of region-based spatial models

Variable	East		Middle		West	
	Coefficient	*P*	Coefficient	*P*	Coefficient	*P*
ln*GDP*	1.133***	0.000	0.548**	0.016	0.198	0.399
ln*GDP2*	− 0.038***	0.000	− 0.013*	0.088	− 0.008	0.356
ln*P*	0.169***	0.000	0.465***	0.000	0.375***	0.000
ln*S*	− 0.038***	0.000	− 0.022***	0.001	− 0.021**	0.037
ln*AE*	0.070***	0.000	− 0.210***	0.000	0.103***	0.001
ln*FDI*	− 0.012*	0.066	0.018***	0.001	− 0.031***	0.000
ln*TI*	− 0.350***	0.000	− 0.058**	0.018	− 0.175***	0.000
ln*K*	0.147***	0.000	0.029**	0.034	0.045*	0.050
ln*M*	− 0.059***	0.005	0.039**	0.045	− 0.003	0.883
T	0.004***	0.000	0.002**	0.017	− 0.003***	0.000
*W**ln*GDP*	− 1.882***	0.000	1.921***	0.004	4.835***	0.000
*W**ln*GDP2*	0.049***	0.004	− 0.064***	0.006	− 0.171***	0.000
*W**ln*P*	0.137***	0.000	− 0.234***	0.000	− 0.022	0.406
*W**ln*S*	0.009	0.694	0.031*	0.052	0.068***	0.005
*W**ln*AE*	0.118***	0.006	0.145***	0.001	0.125	0.135
*W**ln*FDI*	− 0.095***	0.000	0.006	0.663	− 0.028*	0.052
*W**ln*TI*	0.115	0.192	0.184***	0.005	0.144*	0.095
*W**ln*K*	0.301***	0.000	− 0.208***	0.000	0.091	0.120
*W**ln*M*	0.049	0.393	− 0.140***	0.004	− 0.215***	0.005
*W***T*	0.002	0.482	− 0.013***	0.000	− 0.006**	0.015
ρ	0.662***	0.000	0.393***	0.000	0.206***	0.000
R^2	0.205		0.150		0.689	

industries to continue to rise. Although material capital investment increases, it has not yet reached the ideal effect. The market scale (ln*M*) in the eastern region reduces haze pollution, and the expansion of the market scale in the central region damages the environment. The coefficient of *W**ln*M* in the central and western regions is significantly negative and has passed the significance test at the 1% level. The market scale of neighboring regions is expanding continuously, which reduces the environmental pressure of the central and western regions. In the eastern and central regions, the coefficients of the traffic factor are positive, but the values are very small: for each 1% increase, haze pollution increases by 0.004 and 0.002, respectively. In the central and western regions, the convenient transportation in neighboring areas has also reduced haze in the region.

Conclusions and countermeasures

To study the effects of the mechanism and path of economic development and population agglomeration on haze, this paper selects data from 287 cities from 1998 to 2016 and conducts an empirical analysis using the spatial Durbin model through the WALD, LR, and LM tests. At the same time, cities in China are divided into three regions to study the heterogeneity of haze pollution. The main results are as follows:

1 From the empirical results and correlation tests, it can be concluded that haze causes spillover in space. Haze pollution in most areas appears to follow the phenomenon of H-H and L-L concentrations.
2 From the perspective of the whole country, the relationship between the economy and haze pollution is an inverted U-shaped curve. From the results of regional heterogeneity, the relationship is an inverted U shape in the eastern and central regions; there is no obvious relationship between the economy and haze pollution in the western region. By further studying the indirect effects of real GDP and the $PM_{2.5}$ concentration, it is found that the relationship between real GDP in this region and haze in neighboring areas is also an inverted U shape. In all the studies, it is confirmed that population agglomeration has the greatest impact on haze and that it is the primary factor that aggravates haze pollution.
3 On the whole, the coefficients of the industrial structure, technology level, urbanization level, and market scale are negative, which shows that these indexes can improve the atmospheric environment. The coefficient of material capital is positive. The main influencing factors of haze pollution in the eastern area are foreign direct investment and the market scale, which can reduce haze pollution. In the central region, with the acceleration of urbanization and the continuous expansion of the market scale, pollution has been improved, while the increase of foreign investment has placed pressure on the environment. Traffic factors in the western region can improve the environment.

According to the above conclusions, the following policy suggestions are made:

1. Whether from the perspective of the whole country or individual regions, haze pollution has a significant correlation in space. The respective management mode cannot fundamentally solve the problem of environmental pollution. Each region should not be limited locally but should instead cooperate with surrounding areas to realize the governance mechanism of "joint prevention and control."
2. Attentions should be paid to the balance between the economy and the environment. Some cities have passed the inflection point of economic development and should continue to follow the green development route. Cities that have not reached the inflection point should strengthen government supervision, pay attention to environmental protection while developing their economy, and improve the green innovation ability of enterprises. The appraisal of China's performance is based on GDP, which makes local governments only pay attention to economic development without considering environmental issues. Therefore, the local environmental quality should be included in the scope of the performance appraisal to quantify environmental losses, deduct the environmental cost in GDP, and change the traditional concept of attaching importance to the economy and ignoring the environment, thus realizing the decoupling of the economy and haze as soon as possible.
3. Cities in the eastern region have basically entered the late stage of industrial development, but haze pollution still has a spillover effect, which shows that it is difficult for the eastern region to improve air pollution alone. Therefore, the government should break the boundary restrictions of cities, divide pollution areas according to $PM_{2.5}$ data, and determine urban agglomerations of haze pollution. Cities should cooperate with each other and put forward new policies in terms of air quality standard improvements, the pollution management framework and mode, air quality monitoring, compensation, etc. For the central region, we should learn from the rich experience of the east to accelerate the transformation of the industrial structure, eliminate high-pollution industries, improve the environmental entry standards of enterprises, strictly restrict the entry of foreign-funded enterprises with high pollution into the region, and introduce enterprises with low pollution and adhere to green development. In the western region, increasing road construction and convenient transportation can attract more investments, but at the same time, we should learn from the experience of the

eastern and central regions and improve the environmental access standards of enterprises.

4. Optimize the industrial structure, improve the technical level, and accelerate the transformation from labor-intensive to technology-intensive industry. We should vigorously develop a circular economy, use advanced technology to transform traditional industries, enhance the innovation capacity of traditional enterprises, eliminate heavy industries with high pollution, and focus on developing green industries. The government should increase its investment in scientific and technological research and development, change the energy structure, vigorously develop new sources of energy, reduce the use of coal resources with high pollution, and strengthen research on the UHV power grid and energy storage technology. In addition, we should increase research on clean conversion technology for coal and realize the recycling of coal gasification through scientific and technological innovation.
5. Because population agglomeration is the primary factor affecting haze pollution, cities should reasonably control their population density, shifting the focus of haze management from population control to actively promoting pollution source management and optimizing population structure. We should reasonably arrange the population distribution of cities, establish compact cities, pay attention to scientific spatial planning, and constantly improve the quality and level of public services. We should properly expand urban agglomerations, give scope to the economic advantages brought by population and capital accumulation in large cities, and maximize the spillover effect of haze pollution control technologies. The governance of haze pollution requires the participation of the whole population. People should pay attention to saving resources in their daily life and production activities, advocate for a low-carbon and green life, establish strong environmental awareness, achieve green consumption and travel, and reduce emissions from waste articles in life to protect the atmospheric environment and reduce the occurrence of haze weather.
6. The governance of haze pollution is a long-term project, which is the public's demand for improving the quality of the environment, and also provides a good opportunity to promote China's green development, economic structure optimization, and technical level improvement. From a legal perspective, national environmental protection legislation should be strengthened, laws should be improved, regulations and policy standards on atmospheric governance should be implemented, environmental taxes, resource taxes and other means of environmental regulation should be collected, environmental access threshold of enterprises should be improved, and the introduction of high-pollution and high-energy consumption technologies should be limited.

Shortage and prospect

First, this paper uses data on prefecture-level cities. Because of the limited data sources and some missing data, we can only use data on 287 prefecture-level cities for this research, which cannot reflect the haze situation of each city. In addition, haze has many influencing factors. This paper only analyzes haze from the perspective of the economic society. In addition to the influence of economic factors, natural conditions such as wind and temperature also have a certain influence on haze, which makes the research of this paper not completely accurate. The relationship between haze pollution and economic development is actually a two-way relationship. This paper only studies haze from economic development and does not consider the reaction of haze to the economy, which provides direction for follow-up research. The research on haze pollution is a long-term process. The exploration of $PM_{2.5}$ still needs long-term data accumulation and frontier research methods, and the influencing factors and paths of $PM_{2.5}$ need to be further strengthened and improved.

Authors' contributions TG: data curation, formal analysis, writing—original draft, writing—review and editing.

HCY: data curation, formal analysis.

WL: project administration, funding acquisition, conceptualization, supervision.

XCL: conceptualization.

All authors read and approved the final manuscript.

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Data availability The datasets generated and analyzed during the current study are not publicly available due to relative requirements of financially supporting projects but are available from the corresponding author on reasonable request.

Compliance with ethical standards

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare that they have no competing interests.

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