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Spatio-temporal Characteristics and Geographical Determinants of Air Quality in Cities at the Prefecture Level and Above in China

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Abstract: In recent years, the large scale and frequency of severe air pollution in China has become an important consideration in the construction of livable cities and the physical and mental health of urban residents. Based on the 2016-year urban air quality index (AQI) data published by the Ministry of Environmental Protection of China, this study analyzed the spatial and temporal characteristics of air quality and its influencing factors in 338 urban units nationwide. The analysis provides an effective scientific basis for formulating national air pollution control measures. Four key results are shown. 1) Generally, air quality in the 338 cities is poor, and the average annual values for urban AQI and air pollution in 2016 were 79.58% and 21.22%, respectively. 2) The air quality index presents seasonal changes, with winter > spring > autumn > summer and a u-shaped trend. 3) The spatial distribution of the urban air quality index shows clear north-south characteristic differences and a spatial agglomeration effect; the high value area of air pollution is mainly concentrated in the North China Plain and Xinjiang Uygur Autonomous Region. 4) An evaluation of the spatial econometric model shows that differences in urban air quality are due to social, economic, and natural factors.

Keywords: air quality index; spatio-temporal laws; influencing factors; China

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1 Introduction

Since the reform and opening up, China's rapid urbanization and socio-economic development have made remarkable achievements. The level of urbanization and the gross national product increased from 17.9% and 365.02 billion yuan (RMB) in 1978 to 54.7% and 63 404.33 billion yuan (RMB) in 2014. The rapid accumulation of national wealth has also caused significant resource and energy consumption, resulting in a substantial increase in air pollutant emissions and long-term serious harm to the quality of life and physical and mental health of urban residents in China. In the autumn of 2013, a wide range of haze weather that swept across the central and eastern regions of China caused the general public attention to focus sharply on urban air quality. Concurrently, increasingly severe urban air quality problems have forced the national government to seriously consider the traditional extensive economic development mode, gradually increase the supervision of the national urban air quality, and address urban air quality levels as an important component of the government work plan. Premier of China Li Keqiang made a clear request in the 2016 government work report that the air quality good days' ratio of the cities at the prefecture level and above should reach 80% during the '13th Five-Year' period. Therefore, accurately describing the spatial and temporal characteristics of air quality in cities at the prefecture level and above during the 13th Five-Year Plan period and revealing the relevant

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factors of their geospatial correlation have important policy and practical significance for scientific regulation and control of urban air pollution in China.

Due to the increasingly severe and widespread urban air pollution in China, research results on the temporal and spatial laws and influencing factors of urban air quality have also made rapid progress. Due to the short history of the 2012 latest national ambient air standards, the time scale covering PM 2.5 and other important pollutants in urban air quality research is generally of short duration and studies have focused on single year or short-year comparisons (Zhao et al., 2014; Niu et al., 2016). Furthermore, the spatial and temporal scope of air quality research in different cities varies significantly. Research areas have involved different scales, such as national sample cities (Wang et al., 2014; Sheng et al., 2016; Zhang et al., 2016; Wang and Liu, 2016), key cities for environmental protection (Duan et al., 2008; Meng et al., 2012), major urban agglomeration areas (Li et al., 2011; Sun et al., 2012; Ma et al., 2016a), and a few large cities (Zhang et al., 2013; Wang et al., 2015). However, a complete study of urban air quality remains lacking.

The factors influencing urban air quality in China have been the focus of scholars and many studies have focused on the impact of socio-economic drivers on urban air quality, such as per capita GDP, population density, urbanization level, proportion of secondary industry, car ownership, and energy structure (Zhang et al., 2015; Lin and Wang, 2016; Yang et al., 2016; Zhou and Fan, 2016). Some studies have revealed the correlation between natural factors and urban air quality, such as land use type, elevation, and meteorological conditions (Chen et al., 2015; Li et al., 2015; Xu et al., 2015). However, a comprehensive evaluation of the combination of socio-economic factors and natural elements has not been performed sufficiently and the relative importance of each factor has not been considered.

Common measurement methods for urban air quality include $PM_{2.5}$ (Ma et al., 2016b), PM10 (Li et al., 2013), O_3 (Wang et al., 2014), and other individual pollutant indicators. Additional measures include the air quality index (Li et al., 2012; Bao et al., 2015), air pollutants, and other comprehensive indicators (Hu et al., 2014; Zang et al., 2015). The air quality index is a generalization of concentrations of various air pollutants, such as urban SO_2, NO_2, CO, O_3, PM10 and PM2.5, and better reflects the comprehensive characteristics of urban air quality. Here, the air quality index of cities at the prefecture level and above published by China's Ministry of Environmental Protection in 2016 is analyzed in conjunction with socio-economic and natural elements data to comprehensively analyze the spatial and temporal characteristics of air quality in 338 cities using descriptive statistics. GIS spatial analysis and spatial econometrics methods are used to reveal the geo-spatial determinants of urban air quality in China, which can be used as a reference for national urban air pollution control decisions.

2 Data Collection and Methodology

2.1 Data collection

Great efforts have been made by the Chinese government to monitor ambient air quality. In 2012, the Ministry of Environmental Protection enacted the 3rd amendment to the National Ambient Air Quality Standards (NAAQS), promulgated the Ambient Air Quality Standards (GB3095-2012), and recruited new indicators, including $PM_{2.5}$ and O_3 concentration limits within 8 hours. The monitoring system for ambient air quality in urban areas has been improved gradually after the issue of the new standards. In 2012 only 74 cities were monitored, and they were mainly municipalities and provincial cities in Beijing-Tianjin-Heibei Region, Yangtze River Delta, and Pearl River Delta. In 2013, the monitoring area expanded to 113 cities, bringing in the key cities for environmental protection and the national environmental protection model city. In 2014, the scope of monitoring further expanded to 140 cities nationwide and in 2015, the system covered all prefecture-level cities for the first time in history, which provides good data support for the exploration of spatio-temporal regulations of ambient air quality in all of the monitored cities.

The data used in this study were collected from nationwide environment monitoring stations at all levels issued by the Ministry of Ecology and Environment Data Center (http://datacenter.mep.gov.cn/websjzx/queryIndex.vm). The data span the entirety of 2016. Some county-level cities were removed because they overlapped with administrative regions of their prefecture-level cities. As a result, the total number of urban cities employed in this study was 338, covering all cities in China.

The Air Quality Index (AQI) is a non-dimensional index that quantifies urban air quality and acts as a comprehensive parameter for the overall air pollution level of a city. The equation is as follows:

$$AQI = \mathrm{Max}(IAQI_1, IAQI_2, IAQI_3, \cdots IAQI_n) \quad (1)$$

where, AQI represents air quality index; IAQI represents individual air quality index; n represents number of pollutants including sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), particulate matters with particle sizes less than or equal to 10 m (PM_{10}); and particulate matters with particle sizes less than or equal to 2.5 m ($PM_{2.5}$).

Table 1 is a summary of the relevant indicators in the air quality index. A lower air quality index for a city represents a higher level of air quality or better air quality and vice-versa. An AQI value > 100 indicates a certain degree of air pollution in urban air quality in the day, with higher health hazards to residents and more concern from local city residents.

The influencing factors for urban air quality in China include 10 explanatory variables, which are composed of five natural elements and five social and economic factors. Among the natural elements, urban elevation (Digital Elevation Model, DEM) and normalized vegetation index (Normal Differential Vegetation Index, NDVI) were derived from geo-spatial data cloud web sites and precipitation, wind speed, and other meteorological elements were obtained from the Chinese meteorological data network. According to data from national meteorological stations, average meteorological variable values for each city unit were obtained using kriging spatial interpolation and regional statistic means, with specific operations completed using ArcGIS 10.2 software. In view of the availability of social and economic variables at the national level, socio-economic explanatory variables include resident population, GDP per capita, civilian car ownership, and the secondary ratio from the 2014 China Regional Economic Statistics Yearbook. Urbanization level data were obtained from the China 2010 Census County Data using the number of urban and resident populations.

2.2 Methods

2.2.1 Global spatial autocorrelation analysis

The index of air quality was characterized spatially using spatial autocorrelation across the whole study area, i.e., the spatial correlation of air quality was tested using city units. Moran's I statistic was used as the main indicator of spatial autocorrelation from the following equation:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\sum_{j=1}^{n}(x_i - \bar{x})^2} \quad (2)$$

where, n is the number of city units in the research area, a total of 338; x_i and x_j respectively express the AQI numerical value for a city unit i and j; $\bar{x}$ represents the average value of AQI in all cities; and w_{ij} shows the matrix of spatial adjacency. The value range for Moran's I is [–1, 1]. When Moran's $I < 0$, the Chinese city AQI has a spatial negative correlation; when Moran's $I > 0$, the urban AQI is positively related to space; and when Moran's $I = 0$, the urban AQI is distributed randomly and does not have spatial correlation.

2.2.2 Autocorrelation analysis of local space

Local Moran's I analysis (LISA) is a local spatial autocorrelation analysis method, which primarily identifies spatial heterogeneity and the dependence of each spatial object attribute in local space. The calculation formula is

$$I_i = \sum_{j=1, j\neq i}^{n} W_{ij} Z_i Z_j \quad (3)$$

Table 1 Air quality index profile

Air quality index (AQI)	Air quality index level	Air quality index category	Primary pollutant
0–50	Level 1	Excellent	SO_2, NO_2
51–100	Level 2	Good	CO, O_3
101–150	Level 3	Mild pollution	PM_{10}, $PM_{2.5}$
151–200	Level 4	Moderate pollution	
201–300	Level 5	Severe pollution	
>300	Level 6	Serious pollution	

where, Z_i and Z_j are the normalized spatial object attribute values. W_{ij} is the spatial weight between factor i and j. n is the total number of elements. The local spatial autocorrelation results can be divided into four types: high area (High-High, HH), low-low region (Low-Low, LL), low and high (Low-High, LH), and high and low region (High-Low, LL). The first two regions denote spatially dependent areas and the latter two types represent spatially heterogeneous areas.

2.2.3 Method for spatial econometric analysis

Because the spatial correlation between samples is not considered in the general linear regression model, a biased model estimation coefficient may be used in the regression modeling. The spatial econometric analysis method has improved the ordinary linear regression model, considering the spatial correlation of the independent and dependent variables, such that the regression estimation coefficient is more accurate. Common spatial econometric models include the Spatial Lag Model (SLM) and Spatial Error Model (SEM). The general formula for the spatial econometric model is as follows:

$$y = \rho W_1 y + X\beta + \varepsilon \tag{4}$$

$$\varepsilon = \lambda W_2 \varepsilon + \mu \tag{5}$$

where y is the dependent variable, the mean value of the AQI year in China's cities is in 2016; X and β respectively express the explanatory variables and the corresponding coefficients; W_1 is the spatial weight matrix, which reflects the spatial trend of the dependent variables, ε is the random error term, W_2 is the spatial weight matrix of the residual, and μ is the random error of the normal distribution. It is important to note that when $\rho \neq 0$ and $\lambda = 0$, the spatial econometric model is a spatial lag model, which indicates that there is a spatial agglomeration effect between adjacent space objects, and the value of ρ represents the spatial concentration intensity. In contrast, when $\rho = 0$ $\lambda \neq 0$, the spatial econometric model is the spatial error model, which λ indicates the spatial agglomeration intensity between regression residuals.

Anselin proposed a criterion for the spatial econometric model. If the Lagrange multiplier test of the spatial lag model LM-lag is more statistically significant than the Lagrange multiplier test of the spatial error model, the spatial lag model is selected, and the phase is inverse. This indicates that the LM-error is more statistically important than LM-lag and the spatial error model is selected. If the two are not significant, the OLS regression analysis is recommended.

3 Results

3.1 Statistics for urban air quality in China

Fig. 1 is a boxplot of China's urban air quality index. As shown, the AQI average for 338 cities in China was 79.58 in 2016, reflecting the overall low air quality in China. According to the air pollution days scale (AQI > 100 d), China's urban AQI was 21.22%, indicating that the proportion of air pollution days was high and average exposure duration was longer than 20% of the whole year. Among the cities, the annual average AQI and percentage of air pollution days in Kashgar Prefecture were both the highest, at 208.73 and 78.02%, respectively. Panzhihua, Aba Prefecture, Altay Prefecture, Chuxiong Prefecture, Nyingchi Prefecture, Ngari Prefecture, and Lijiang had the lowest proportion of air pollution days, all 0 indicating that these cities had air quality that was relatively good and far beyond the general standard.

3.2 Temporal air quality characteristics for Chinese cities

Fig. 2 shows the characteristics of China's urban air quality index in different months in 2016. As shown, the mean AQI value and its standard deviation varied by month, showing a clear u-shaped feature. The average AQI starts declining in January and reaches low points in July and August, with AQI averages of 64.65 and

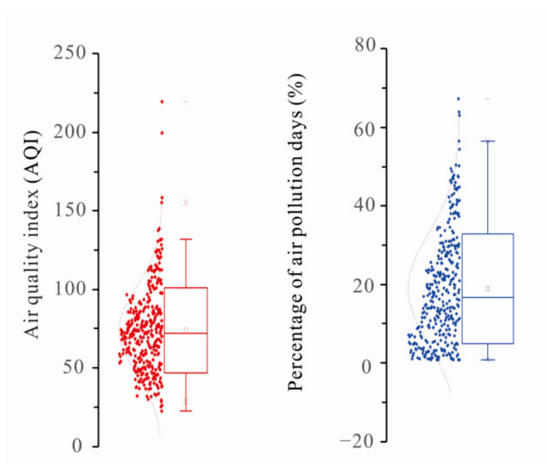

Fig. 1 Box line chart for air quality in Chinese cities in 2016

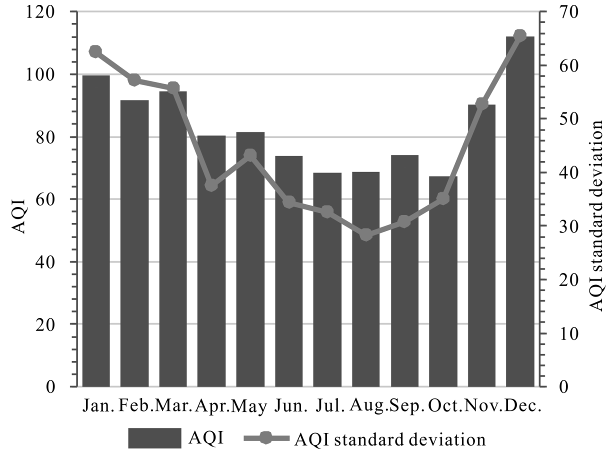

Fig. 2 Characteristic air quality for each month in China in 2016

64.73 respectively. In September, the average AQI value recovers slightly, and the average AQI drops to the lowest value in October, with a value of 63.52. The number then gradually increases and peaks in December at 108.22. Seasonal statistics show that China's average urban AQI presents a trend of winter > spring > autumn > summer, with corresponding average AQI values of 97.26, 81.61, 73.38, and 66.39, respectively. The urban air quality index is characterized by the highest percentage of fine weather occurring mainly in the summer months, with light pollution in every month throughout the year and more than the moderate pollution in winter, early spring, and late autumn.

3.3 Spatial characteristics of urban air quality in China

Fig. 3 (left) shows the spatial distribution of mean AQI in Chinese cities in 2016. China's urban AQI average shows a significant spatial difference between the north and south. The average AQI values for cities south of the Yangtze River are significantly lower than those in the southern region, which indicates that air pollution is more serious north of the Yangtze River in 2016. China's urban high value AQI areas are mainly distributed in the north China Plain region or municipalities directly under the central government, such as Beijing, Tianjin, and Shandong Provinces; the northwestern region of the Xinjiang Uygur Autonomous Region; and the central region within the territory of Henan and several cities in Hubei and Anhui Provinces. China's urban low value AQI areas are mainly concentrated in Tibet, Sichuan, Yunnan, Guizhou, and Guangxi; the southern provinces, such as Guangdong and Fujian; and Heilongjiang, Inner Mongolia, and other northern provinces. A few cities distributed in the northwestern Xinjiang Uygur Autonomous Region also show low AQI values.

Global spatial autocorrelation analysis results show that in 2016, China's urban AQI had a significant positive spatial relationship, with a Moran's I value of 0.761 and p value that passed the 0.05 confidence level significance test. These results show that China's urban air quality is strongly affected by spatial agglomeration with adjacent cities. In addition, the seasonal urban AQI values are significant positively related to space, with Moran's I values for spring, summer, autumn, and winter of 0.699, 0.670, 0.699, and 0.699, respectively. Each season shows different levels of the spatial agglomeration effect, with a significantly stronger spatial agglomeration effect in winter, and lower effect in summer.

Fig. 3 (right) shows a local spatial autocorrelation model for AQI in Chinese cities. As shown, the high value AQI agglomeration area is mainly concentrated in the north China Plain and Xinjiang Uygur Autonomous Region. The low value AQI agglomeration area is more distributed in Fujian, Guangdong, Guangxi, Yunnan, and Guizhou Provinces, with some local areas in Jiangxi, Sichuan, Tibet, Heilongjiang, and Inner Mongolia.

Fig. 4 shows the local spatial autocorrelation patterns for urban AQI in different seasons where different seasons show clear low-south and high-north distribution characteristics. The high AQI high concentrated area (HH) is mainly concentrated in the north China Plain and the Xinjiang Uygur Autonomous Region and the low AQI low convergent zone (LL) is mainly distributed in the south, southwest, and northeast regions of China. However, the AQI high value accumulation and low concentration areas change seasonally. In spring, a large number of urban units are in the smallest and low-value cluster areas within the AQI high value cluster area, 36 and 81, respectively. In summer, the number of AQI high value agglomeration areas increase significantly, to 57, and the cities are mainly distributed in the Inner Mongolia Autonomous Region. In autumn, the AQI high value agglomeration area and low-value agglomeration area cities both decrease, to 54 and 59, respectively. In winter, the AQI high value and low value agglomeration areas include the largest number of cities.

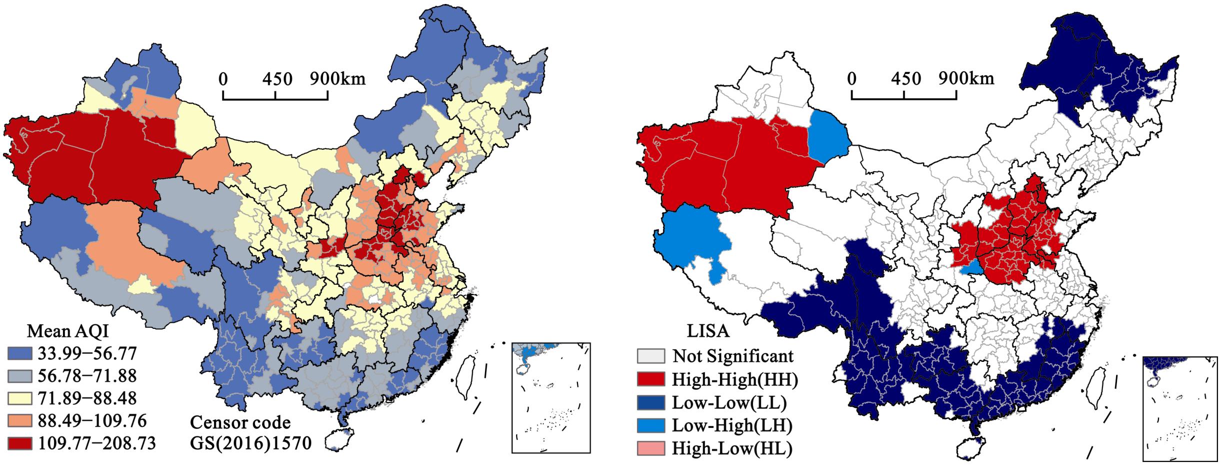

Fig. 3 Spatial distribution and autocorrelation patterns of urban AQI in China

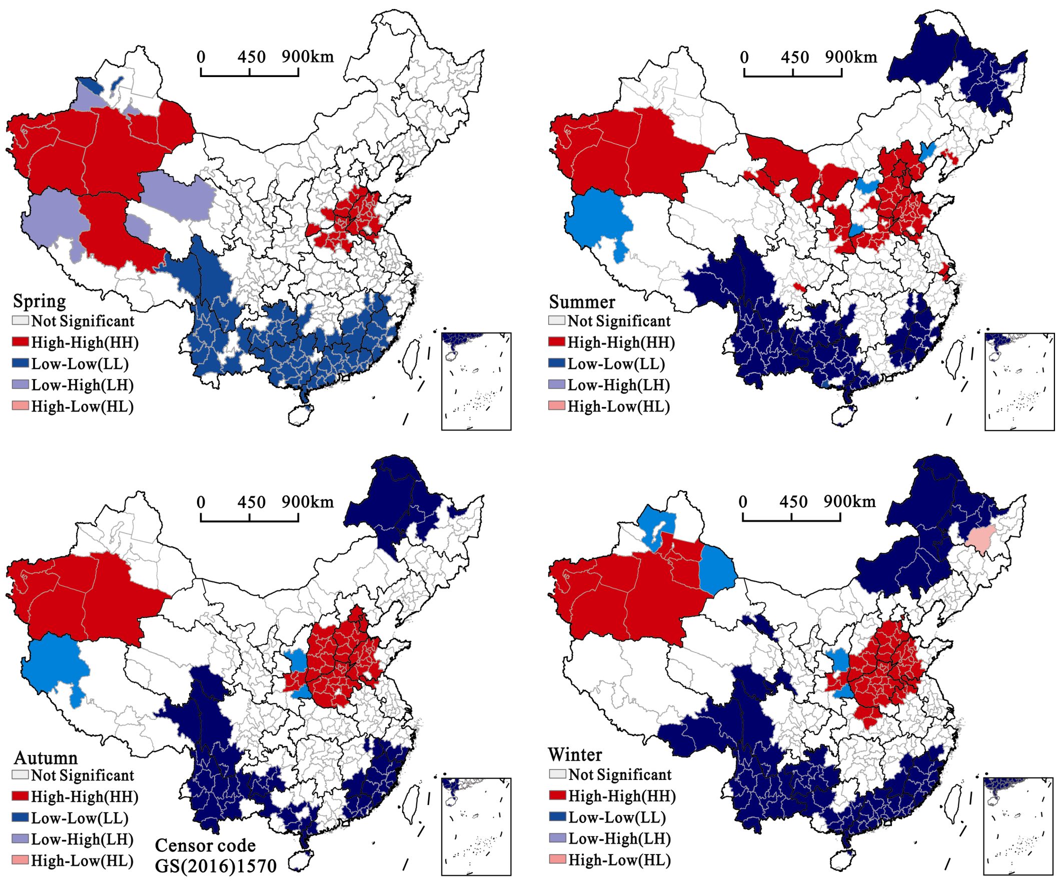

Fig. 4 Local spatial autocorrelation model of seasonal urban AQI in China

3.4 The influencing factors for spatial differences in urban air quality in China

The model for the empirical analysis of the factors influencing urban air quality in China is based on the AQI average annual values for 338 urban units in China in 2016 and explanatory variables, including DEM, NDVI, temperature, precipitation, wind speed, resident population, GDP per capita, secondary ratio, civilian car ownership, and urbanization level. Even before modeling, there is a strong correlation between the population of Chinese cities and resident populations and between the precipitation and temperature variables. The VIF value of these variables corresponds to five in the normal linear regression model, which indicates that there may be collinearity between the original variables. Therefore, two variables for civil car ownership and precipitation are deleted and eight explanatory variables are run in the ordinary OLS regression model again. The VIF results for each interpretation variable conform to the requirements, and the explanatory variables in the model do not have collinearity.

Model 1 in Table 2 is a general linear regression model, and the least squares method is used for estimates. Model 1 shows that the regression equation model is significant, with an F value of 24.56, and the significant level of 1 is tested. The coefficients from the OLS model indicate that only the effect of GDP per capita is not significant, and the resident population and secondary proportion have positive influences on the urban AQI of China. The urbanization level, DEM, NDVI, air temperature, and wind speed explanatory variables have obvious mitigating effects on urban AQI. However, because the general linear regression model does not consider the spatial correlation of urban air quality, the estimation results from the model may be biased. Therefore, the spatial correlation of the residual error of the ordinary linear regression model must be evaluated. Table 3 shows that the residual error of the general linear retrospective model is spatially correlated, and the robust LM (lag) is more significant than the robust LM (error); therefore, the spatial hysteresis model is more appropriate.

Model 2 in Table 2 is the spatial lag model (SLM), where the maximum likelihood method is used for estimates. The SLM model fitting results show that the R2 and likelihood values of the SLM model both increase and the AIC value decreases compared with the OLS model, which shows that the overall fit of the SLM model is better than that of the normal OLS model. The estimated coefficient for the SLM model shows that an increase in urban population can increase the AQI, making it easy to reduce urban air quality. Urban population can be a good representation of human social and economic activities. Large cities usually have greater populations, with higher intensity social and economic activities that increase resource energy consumption and air pollutant emissions. The proportion of secondary industry also has a positive effect on the urban AQI because its consumption intensity is relatively large and is an important source of air pollutants; a higher proportion of urban secondary production generally reduces urban air quality.

Higher urban elevation has an inhibitory effect on the urban AQI and results in better urban air quality. This may be because China's high altitude urban terrain is relatively flat, so the higher wind speed combined with lower human social and economic activity not conducive to the accumulation of air pollutants. The normalized vegetation index also showed a significant negative correlation with the urban AQI in China because a

Table 2 Influencing factors driving differences in urban AQI in China

Variables	Codes	Model 1: OLS			Model 2: SLM		
		B	*T* value	*P* value	B	*Z* value	*P* value
W_AQI					0.81^{***}	25.67	0.00
CONSTANT	C	83.97^{**}	2.44	0.02	12.35	0.63	0.53
Population (Ln)	POP	12.58^{***}	8.02	0.00	6.04^{***}	6.74	0.00
Per capita GDP (Ln)	PGDP	2.16	0.58	0.56	1.02	0.49	0.62
Percentage of second industry	PSI	45.92^{***}	3.94	0.00	14.44^{**}	2.19	0.03
Urbanization rate	UR	-36.00^{***}	–3.29	0.00	–4.28	–0.70	0.49
Dem (Ln)	DEM	-0.01^{***}	–5.01	0.00	-0.003^{***}	–2.73	0.01
NDVI	NDVI	-64.26^{***}	–7.94	0.00	-24.58^{***}	–5.12	0.00
Temperature	TEM	-1.84^{***}	–7.14	0.00	-0.61^{***}	–3.92	0.00
Wind	WIND	-10.07^{***}	–2.57	0.01	-8.25^{***}	–3.62	0.00
R-squared		0.374			0.799		
Log likelihood		–1473.66			–1312.37		
AIC		2965.31			2644.74		

Notes: * indicates significant confidence level at 0.1 level, ** indicates significant Confidence level at 0.05 level, *** indicates significant Confidence level at 0.01 level

Table 3 Diagnostics for spatial dependence

Test	MI/DF	Value	*P* value
Moran's *I* (error)	0.6123	18.545	0.000
Lagrange Multiplier (lag)	1	353.1087	0.000
Robust LM (lag)	1	50.3481	0.000
Lagrange Multiplier (error)	1	305.4847	0.000
Robust LM (error)	1	2.7241	0.099
Lagrange Multiplier (SARMA)	2	355.8328	0.000

higher vegetation coverage index results in a stronger absorption and sedimentation of air pollutants in a city, which improves the atmospheric environmental quality. It has been widely proven that temperature has a significant negative effect on the AQI in China, mainly because rising temperatures promote the vertical convection of the atmosphere, which is conducive to the diffusion of air pollutants and better air quality. Wind speed is also a significant factor in the urban AQI in China; it generally lowers the urban AQI because it provides good dilution and diffusion effects.

4 Conclusions and Implications

Four main conclusions were obtained from this study:

The overall air quality of Chinese cities is poor, with a high average frequency of air pollution. In 2016, the above prefecture level cities in China had average AQI and air pollution day ratios of 79.58 and 21.22%, respectively. Therefore, China's urban air pollution control task remains challenging and the nation needs to continue to increase investments in atmospheric environment protection.

China's urban air quality index shows a typical seasonal variation pattern. The AQI has a u-shape characteristic over the year, with the average AQI having a trend of winter > spring > autumn > summer. Therefore, the Chinese government should focus on measures to address the air pollution particularly in winter in China, such as restricting the production of high-polluting enterprises and adopting motor vehicle controls.

Spatially, China's urban AQI is characterized by lows in the south and highs in the north; the high value cluster areas are mainly concentrated in the north China Plain region and Xinjiang Uygur Autonomous Region, and the low value concentrated areas are generally in the south, southwest, and several northeast areas.

The agglomeration areas are similar across the seasons, but there are some spatial variations. The highly focused regions are in north China and northwest of Xinjiang Uygur Autonomous Region. To speed up regional urban industrial structure upgrades and technological innovation, clean energy should be actively promoted, which will help alleviate the local urban air pollution situation. Furthermore, because China's urban air pollution has a strong spatial agglomeration effect, we should strengthen regional coordinated development, accelerate the establishment of a scientific and reasonable system for the regional industry division of labor, implement a national ambient air quality scheme using ecological compensation, mitigate urban air pollution zones from spreading, break administrative divisions for air pollution prevention, and publicize so that every local city participates in air pollution control.

The results of the spatial econometric model show that spatial differences in the urban AQI in China are primarily influenced by comprehensive driving forces, such as socio-economic and natural factors. Among them, social and economic factors, i.e., urban population and the proportion of second industry, have a positive influence on the AQI, which results in lower urban air quality. Natural factors, such as urban DEM, NDVI, temperature, and wind speed have significantly reduced the urban AQI. Controlling the population size of China's mega-cities and promoting the development of tertiary industries can help control the absolute quantity of air pollutant emissions from the source. Concurrently, based on the influence from natural factors showing that northern low temperatures effect air pollutant emissions, phasing out and decreasing the number of heavy chemical polluting industries in northern cities should improve China's urban air quality.

References

Bao J Z, Yang X P, Zhao Z Y et al., 2015. The spatial-temporal characteristics of air pollution in China from 2001–2014. *Environmental Research and Public Health*, 12(12): 15875–15887. doi: 10.3390/ijerph121215029

Chen Yonglin, Xie Binggeng, Yang Yong, 2015. Distribution of the urban air quality in the major city clusters in China and the influencing factors. *Journal of Arid Land Resources and Environment*, 29(11): 99–103. (in Chinese)

Duan Yusen, Wei Haiping, Fu Qingyan et al., 2008. Regional spatio-temporal mode differences of air pollution index of key environmental protection cities in China. *Acta Scientiae Circumstantiae*, 28(2): 384–391. (in Chinese)

Hu J L, Wang Y G, Ying Q et al., 2014. Spatial and temporal variability of $PM_{2.5}$ and PM_{10} over the North China Plain and the Yangtze River Delta, China. *Atmospheric Environment*, 95: 598–609.

Li Mingsheng, Zhang Jianhui, Zhang Yinjun et al., 2013. Spatio-temporal pattern changes of ambient air PM_{10} pollution in China from 2002 to 2012. *Acta Geographica Sinica*, 68(11): 1504–1512. (in Chinese)

Li Song, Luo Xueqiang, Li luan et al., 2015. Spatial distribution model of countrywide $PM_{2.5}$ concentration and influence factors using geographical information system. *Bulletin of Soil and Water Conservation*, 35(4): 202–205, 212. (in Chinese)

Li Wenjie, Zhang Shihuang, Gao Qingxian et al., 2012. Relationship between temporal-spatial distribution pattern of air pollution index and meteorological elements in Beijing, Tianjin and Shijiazhuang. *Resources Science*, 34(8): 1392–1400. (in Chinese)

Li Xiangyang, Ding Xiaomei, Gao Hong et al., 2011. Characteristics of air pollution index in typical cities of North China. *Journal of Arid Land Resources and Environment*, 25(3): 96–101. (in Chinese)

Lin Xueqin, Wang Dai, 2016. Spatio-temporal variations and socio-economic driving forces of air quality in Chinese cities. *Acta Geographica Sinica*, 71(8): 1357–1371. (in Chinese)

Ma Xiaoqian, Liu Zheng, Zhao Xueyang et al., 2016a. The spatial and temporal variation of haze and its relativity in the Beijing-Tianjin-Hebei region. *Areal Research and Development*, 35(2): 134–138. (in Chinese)

Ma Z W, Hu X F, Sayer A M et al., 2016b. Satellite-based spatiotemporal trends in $PM_{2.5}$ concentrations: China, 2004–2013. *Environmental Health Perspectives*, 124(2): 184–192. doi: 10.1289/ehp.1409481

Meng Xiaoyan, Wang Ruibin, Zhang Xin et al., 2012. Concentration variations of main pollutants in key environmental protection cities in China during 2006-2010. *Research of Environmental Sciences*, 25(6): 622–627. (in Chinese)

Ministry of Ecology and Environment Data Center. Available at: http://datacenter.mep.gov.cn/websjzx/queryIndex.vm. (in Chinese)

Niu Huimin, Tu Jianjun, Yao Zuolin et al., 2016. Spatial and Temporal Distribution Characteristics of Air Quality in China's Cities. *Henan Science*, 34(8): 1317–1321. (in Chinese)

Sheng N, Tang U W, 2016. The first official city ranking by air quality in China-A review and analysis. *Cities*, 51: 139–149. doi: 10.1016/j.cities.2015.08.012

Sun Dan, Du Wupeng, Gao Qingxian et al., 2012. Change characteristics of API of several typical cities within three urban agglomerations in China from 2001 to 2010. *Resources Science*, 34(8): 1401–1407. (in Chinese)

Wang D, Liu Y, 2016. Spatio-temporal differences and driving forces of air quality in Chinese cities. *Journal of Resources and Ecology*, 7(2): 77–84. doi: 10.5814/j.issn.1674-764x.2016.02.001

Wang Y G, Ying Q, Hu J L et al., 2014. Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013–2014. *Environment International*, 73: 413–422. doi: 10.1016/j.envint.2014.08.016

Wang Zhanshan, Li Yunting, Chen Tian et al., 2014. Temporal and spatial distribution characteristics of ozone in Beijing. *Environmental Science*, 35(12): 4446–4453. (in Chinese)

Wang Zhanshan, Li Yunting, Chen Tian et al., 2015. Spatial-temporal characteristics of $PM_{2.5}$ in Beijing in 2013. *Acta Geographica Sinica*, 70(1): 110–120. (in Chinese)

Xu Shan, Zou Bin, Pu Qiang et al., 2015. Impact analysis of land use/cover on air pollution. *Journal of Geo-Information Science*, 17(3): 290–299. (in Chinese)

Yang Kun, Yang Yulian, Zhu Yanhui et al., 2016. Social and economic drivers of $PM_{2.5}$ and their spatial relationship in China. *Geographical Research*, 35(6): 1051–1060. (in Chinese)

Zang Xinghua, Lu Yintao, Yao Hong et al., 2015. The temporal and spatial distribution characteristics of main air pollutants in China. *Ecology and Environment Sciences*, 24(8): 1322–1329. (in Chinese)

Zhang A, Qi Q W, Jiang L L et al., 2013. Population exposure to $PM_{2.5}$ in the urban area of Beijing. *PLoS One*, 8(5): e63486. doi: 10.1371/journal.pone.0063486

Zhang H F, Wang Z H, Zhang W Z, 2016. Exploring spatiotemporal patterns of $PM_{2.5}$ in China based on ground-level observations for 190 cities. *Environmental Pollution*, 216: 559–567. doi: 10.1016/j.envpol.2016.06.009

Zhang Yinjun, Chen Xi, Xie Gaodi et al., 2015. Pollution status and spatial distribution of $PM_{2.5}$ in China. *Resources Science*, 37(7): 1339–1346. (in Chinese)

Zhao Keming, Li Xia, Lu Xinyu et al., 2014. Wintertime temporal-spatial distribution characteristics of air pollutants in mountain gap town Urumqi. *Arid Land Geography*, 37(6): 1108–1118. (in Chinese)

Zhou Kan, Fan Jie, 2016. Regional disparity of environmental pollution source and its socio-economic influencing factors: Based on the cross-section data of 339 cities at prefecture level or above in China. *Acta Geographica Sinica*, 71(11): 1911–1925. (in Chinese)