Using spatial autocorrelation and spatial autoregressive models to analyze the spatial pattern of aerosol optical depth and the affecting factors

Hua Wang [1*] , YangJie Guo [1], Zhongqiu Liu [1], Yaolin Liu [1] and Song Hong [1]

1 School of Resource and Environmental Science, Wuhan University, Luoyu Road 129, Wuhan 430079, China;

Telephone：+8618986224370；+8613476230662；+8618986247127；+8613871298058；+8613871063859
E-Mails: whuwanghua@163.com (H.W.); 37303036@qq.com(Y.G.); zoneq6@163.com (Z.L.);

yaolin610@163.com(Y.L.); songhongpku@126.com(S.H.)

Abstract

The atmospheric aerosol generally refers to a suspension of liquid or solid particles in the atmosphere, with particle diameters ranging in size over more than four orders of magnitude, from 10^{-9} m to 10^{-4} m [1]. As we know, the aerosols not only influence the energy budget of the Earth, the hydrological cycle, global and regional climate by their direct and indirect radiation forcing but also play an important role in the spreading of biological organisms and pathogens which can cause some serious public health issues, for instance, respiratory, cardiovascular, and infectious diseases [2]. So the atmospheric aerosols have got extensive attention from public and become a hot topic and one of the most forward researches in atmospheric sciences field. To get a better understanding of the influence of aerosols on environment, climate and human health, in recent years, many observational studies have been conducted on the compositions, sources, size distribution, and properties of aerosols [3-8]. Aerosol optical depth (AOD), an important physical parameter for indicating atmospheric turbidity and aerosol content, has also been used by researchers to analyse the characteristics of spatial and temporal distribution variation of tropospheric aerosols in a long-term. For example, Qiu et al [9] analyzed the variation characteristics of AOD and visibility based on the data from five meteorological observatories in north China during 1980-1994; Luo et al [10] made the analysis on the distribution of yearly mean AOD and its variation over China from 1979 to 1990, and found that the yearly mean AOD has pattern related to the geographical features; Herber et al. [11] established the Ground-based measurements of total AOD and discussed the seasonal variation and the long-term trend of tropospheric AOD in the Arctic between 1991 and 1999; Sakerin et al [12] discussed the spatial variability of atmospheric transparency and the spectral behavior of AOD in different oceanic areas over the Atlantic Ocean between 1989 and 1996; Kazadzis et al. [13] observed the seasonal variation of AOD at Thessaloniki, Greece between 1997 and 2005; Plakhina et al [14] revealed the general regularities of spatial variations in the AOD over Russia on the basis of a 30-year (1976-2006) series of observations; Ramachandran et al [15] derived the seasonal and annual mean trends in AOD for the last decade using MODIS aerosol data over different locations in India.

However, the aforementioned studies are confined to the simple comparison analysis of AOD, and neglect the implicit information in the spatial pattern of AOD, such as spatial configuration characteristics, spatial heterogeneity and spatial dependence, the understanding of which is helpful to the accurate estimate of environmental and climatic effects due to aerosols. Nevertheless, related research is rare

reported. Spatial autocorrelation (SA) analysis, one of the Geographical statistical methods, measures the degree of spatial association of a spatial object with the nearby ones when one variable is considered across geo-referenced space [16], and is frequently used to explore the spatial pattern of various geographic object in different fields, such as ecology [17-18], public health [19-20], socioeconomics [21-22], environmentology [23-24], etc. So in this study, the SA approach will be applied to the analysis of spatial pattern of AOD in a regional scale for the first time.

Several earlier studies have shown that landform, population, socio-economic activities have a significant influence on the spatial-temporal pattern of aerosols [25-27] and provide descriptive and qualitative analyses. Guo et al [28] presented quantitative analysis using self-organizing maps (SOMs) and linear regression methods with the assumption of independence of variables. But the probable existence of spatial autocorrelation in AOD, inflating the probability of a type I error in hypotheses tests, may cause an ordinary least squares (OLS) model (correlation, linear regression model) to produce inefficient coefficient estimates[29]. For this reason, spatial regression techniques such as spatial lag model and spatial error model are adopted to control the spatial autocorrelation in AOD [30], and help to correct these estimation problems for effects of some chosen explanatory variables on atmospheric aerosols, what will also help us get a better understanding of the formation mechanism of the spatial pattern of atmospheric aerosols.

So in this study, a method of spatial autocorrelation statistics from geostatistics was applied to investigate the spatial pattern of AOD of Hubei province in central China during 2003-2008, then the spatial autoregressive models were used to quantize the correlations between AOD and affecting factors such as elevation, forest coverage and population density, and the difference between standard linear regression model and spatial models was discussed. The results were as follows: the spatial pattern of AOD in Hubei show significant spatial autocorrelation indicating that AOD are clustered such that higher AOD tend to be surrounded by higher AOD neighbors and lower AOD by lower AOD neighbors (see Table 1 and Figure 2), and spatial autocorrelation scale of AOD over Hubei is about 400km (see Figure 1). The high-high zone is mainly distributed in Wuhan city circle and Jianghan plain areas, the low-low zones are mainly located in the middle and high mountain areas of northwest Hubei (see Figure 2). The overall spatial autocorrelation degree and pattern don’t change greatly from 2003 to 2008 that indicate a stable spatial configuration of AOD (see Table 1). Significant negative spatial autocorrelation is existed between AOD and elevation what may suggest they have an inverse spatial distribution, the same apply for forest coverage; population density and AOD show significant positive spatial autocorrelation, it may imply that they have similar spatial distribution; industrial output and AOD do not show obvious positive spatial autocorrelation (see Figure 3). Spatial autoregressive models show better predictive ability and stability than the standard linear regression model because of the spatial autocorrelation of AOD is taken into consideration (see Table 2 to 5 and Figure 4).

Keywords: aerosol optical depth (AOD), spatial pattern, spatial autocorrelation, spatial autoregressive models, affecting factors, Hubei province

Variable	Moran's I	E[I]	Mean	Sd
AOD2003	0.8533	-0.0118	-0.0107	0.0822
AOD2004	0.8589	-0.0118	-0.0104	0.08
AOD2005	0.8421	-0.0118	-0.0087	0.0817

AOD2006	0.8102	-0.0118	-0.0135	0.0766
AOD2007	0.8481	-0.0118	-0.0092	0.082
AOD2008	0.8495	-0.0118	-0.0093	0.0802

[a] AOD2003 is the AOD of Hubei in 2003, and the same apply for AOD2004, AOD2005, AOD2006, AOD2007, AOD2008.

Table 1 Moran's I coefficient of AOD in Hubei Province during 2003-2008

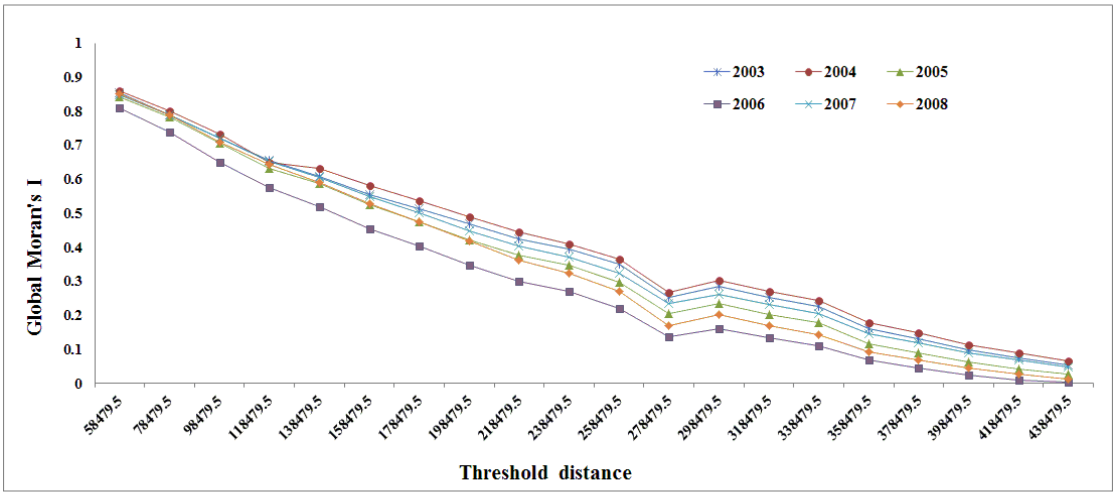

Figure 1 Spatial autocorrelation coefficient of AOD at different threshold distance

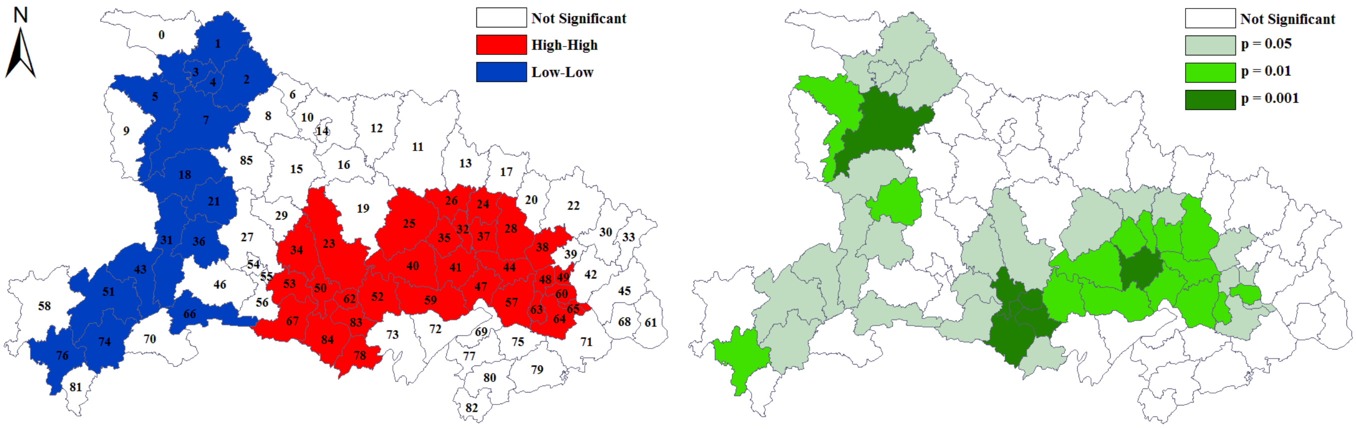

Figure 2 Cluster map and significance map of LISA of 6-year mean AOD over Hubei Province, the number in each polygon shows the ID number of research unit.

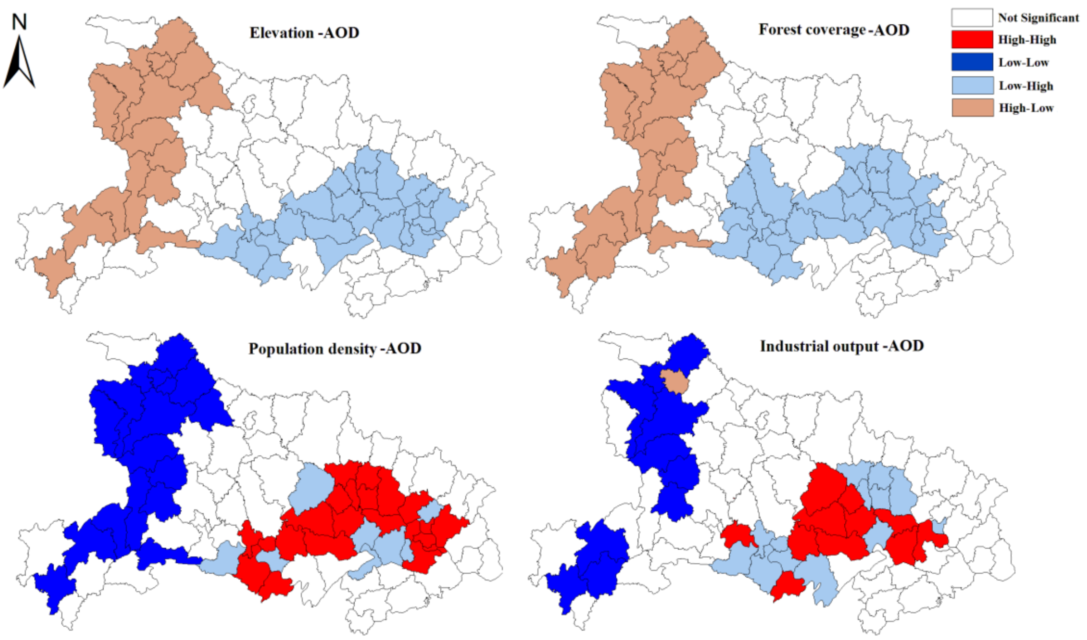

Figure 3 Cluster map of Bivariate LISA of elevation, forest coverage, population density and industrial output with AOD

Explanatory variable	Constant/ p-value	Coefficient of variable / p-value	R^2	LIK	AIC	SC	Moran's I of residual
Elevation	0.6883139/0	-0.0004547201/0	0.748880	73.1238	-142.248	-137.339	0.612683
Forest coverage	0.7951161/0	-0.006066973/0	0.843297	93.4016	-182.803	-177.894	0.364471
Population density	0.1979629/0	0.0009819615/0	0.630546	51.7696	-99.5391	-94.8515	0.431135

Table 2 Calculated model parameters of standard linear model

Explanatory variable	ρ/ p-value	Constant/ p-value	Coefficient of variable / p-value	Pseudo R^2	LIK	AIC	SC	Moran's I of residual
Elevation	0.7566601/0	0.1689454/0.000014	-0.0001410668/ 0.000002	0.904908	105.981	-205.962	-198.599	0.2114
Forest coverage	0.6308326/0	0.3092017/0	-0.002779143/0	0.934862	125.56	-245.12	-237.757	-0.0094
Population density	0.8060978/0	-0.007044153/0.6894908	0.0003121011/0	0.916798	98.1182	-190.236	-183.205	0.0635

Table 3 Calculated model parameters of SLM

Explanatory variable	λ/ p-value	Constant/ p-value	Coefficient of variable / p-value	Pseudo R^2	LIK	AIC	SC	Moran's I of residual
Elevation	0.8547293 /0	0.6026065/0	-0.0003094867/ 0	0.916363	107.659072	-211.318	-206.409	0.0827
Forest coverage	0.8404779/0	0.6444471/0	-0.003428325/0	0.919912	110.186180	-216.372	-211.464	-0.0788
Population density	0.9193764/0	0.3614398/0.0000506	0.000250524/ 0.0002259	0.907627	88.026498	-172.053	-167.365	0.0626

Table 4 Calculated model parameters of SEM

Variable	Coefficient	S.D.	t-value	Probability
(a) multiple linear model				
Constant	0.7427765	0.01817339	40.87165	0
Elevation	-0.0001852035	3.040396e-005	-6.091428	0
Forest coverage	-0.003879846	0.0003936023	-9.857274	0
Population density	4.755744e-005	1.842244e-005	2.581495	0.0116166
R^2	0.900486			
LIK	112.926			
Moran's I of residual	0.3908			
Variable	Coefficient	S.D.	z-value	Probability
(b) SLM model				
ρ	0.5250647	0.0695295	7.551682	0
Constant	0.3569777	0.0525141	6.79775	0
Elevation	-6.560303e-005	2.983853e-005	-2.198601	0.0279062
Forest coverage	-0.002411319	0.000339081	-7.111336	0
Population density	3.748925e-005	1.383938e-005	2.708883	0.0067511
Pseudo R^2	0.9412			
LIK	131.913			
Moran's I of residual	0.0577			
(c) SEM model				
λ	0.6372326	0.08750747	7.282037	0
Constant	0.717287	0.02357217	30.4294	0
Elevation	-0.0002234979	3.662994e-005	-6.10151	0
Forest coverage	-0.002941309	0.0004186215	-7.026178	0
Population density	2.90522e-005	1.385317e-005	2.097152	0.03598
Pseudo R^2	0.935188			
LIK	125.636818			
Moran's I of residual	-0.0391			

Table 5 Calculated model parameters of three different models with multiple variables

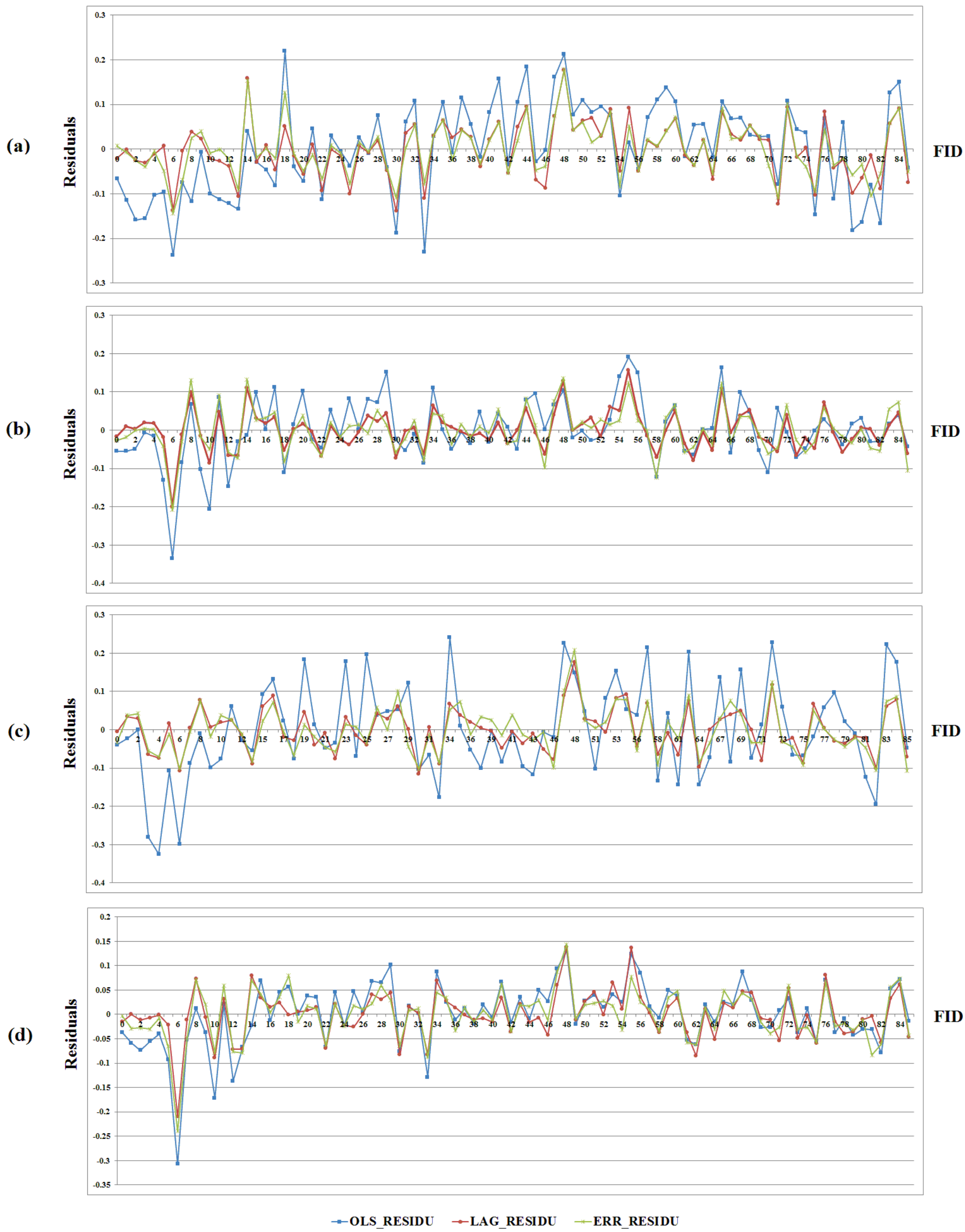

Figure 4 Comparison of the residuals of the standard linear model (OLS_RESIDU), the SLM model (LAG_RESIDU) and the SEM model (ERR_RESIDU): (a) elevation, (b) forest coverage, (c) population density, (d) three factors

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