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Driving forces and the spatial patterns of industrial sulfur dioxide discharge in China

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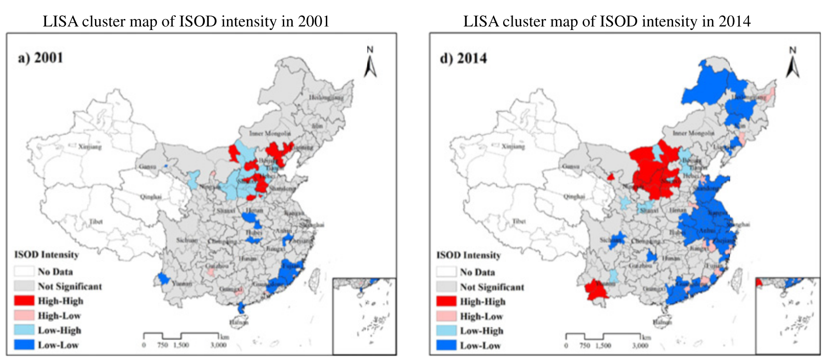
HIGHLIGHTS

- Spatial patterns and driving forces of ISOD in China from 2001 to 2014 are assessed.
- Spatial autocorrelation and spatial regression are used.
- ISOD amount increased first and then decreased.
- ISOD intensity witnessed a fluctuating drop.
- Land use and environmental policy affected the spatial patterns of ISOD.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid industrialization in China has brought forward serious and harmful atmospheric pollution. In this study, spatial econometric analysis was used to analyze the spatial change and the driving forces behind the industrial sulfur dioxide (SO_2) discharge in China from 2001 to 2014. The study found that the amount of industrial SO_2 discharge (ISOD) increased first and then decreased during this period. ISOD intensity witnessed a fluctuating drop. There were large differences among intercity ISOD amount and intensity, which had various spatial patterns. Global Moran's *I* of ISOD amount and intensity had a tendency to increase on the whole, showed positive spatial autocorrelation, and revealed a more and more remarkable clustered spatial pattern. Local spatial autocorrelation analysis found that the spatial patterns of ISOD amount and intensity changed considerably over space and time. The spatial patterns of ISOD were significantly influenced by the regional differences in land use and environmental policy. The study also found that the driving forces of ISOD in China changed significantly from 2001 to 2014.

1. Introduction

Sulfur dioxide (SO_2) is one of the main pollutants in the atmosphere, and it is an important marker for judging whether the atmosphere is polluted. SO_2 discharge endangers human health (Herbarth, 1995).

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The acid rain formed with it has many negative consequences on the ecological system and the environment, including soil, forest, agriculture, and water bodies. It brings heavy losses to society and the economy (Zhao and Hou, 2008). The USA, the UK and Japan have experienced ecological and environmental destruction as well as human health damage as a result of the excessive SO_2 discharge associated with their industrialization process (Li et al., 2010). SO_2 emissions in China contribute to about 25% of the global SO_2 emission and 50% of the SO_2 emission in Asia (Lu et al., 2011), and are the major contributors of $PM_{2.5}$ in China (Pathak et al., 2009; Mo et al., 2013). Since 2000, industrial SO_2 discharge (ISOD) control has been one of the important components of air pollution prevention and control policy.

Rapid industrialization has brought forth tremendous economic benefits to China. However, it has also led to serious and harmful atmospheric pollution. In China, the annual economic loss arising from the damage of the ecological environment and human health caused by acid rain and SO_2 pollution is estimated to be about US $17 billion (State Environmental Protection Administration, 2004). At present, the Chinese government pays more attention to protecting water and air quality, which are closely related to people's health. Since 2005, China has started to control the discharge of sulfur-bearing pollutants, especially SO_2 discharged by power plants and other industrial sources. In 2007, the State Council issued the *Comprehensive Work Plan for Energy Conservation and Emission Reduction* and announced clear objectives for SO_2 and Chemical Oxygen Demand (COD) emission reduction. However, according to the data in the *China Environmental Statistical Bulletin* in 2009, 258 cities among the 488 monitored cities had suffered from acid rain, accounting for 53% of all monitored cities. In 2014, among China's waste gases, the total discharge of SO_2 was 1974×10^4 tons. The discharge of industrial SO_2 was 1740×10^4 tons, accounting for 88% of total SO_2 discharge (Ministry of Environmental Protection, 2014). Therefore, reducing industrial SO_2 discharge (ISOD) is a major element of China's SO_2 emission reduction policy. The continuous presence of heavy smog in the central and eastern regions of China since 2012 has aroused unprecedented attention and has forced China's government to make atmospheric pollution governance a major challenge in its future work.

Air pollution and environmental degradation caused by SO_2 emission have aroused extensive concern around the world. Existing research mainly focuses on three areas. The first area is the relationship between SO_2 discharge and economic growth. Past studies have observed that the relationships between most pollutants and per capita income tend to follow the Environmental Kuznets Curve (EKC) (Grossman and Krueger, 1991; Selden and Song, 1994; Pasqual and Souto, 2003; Roxworthy et al., 2012). The EKC hypothesis proposes that there is an inverted U-shape relation between environmental degradation and per capita income, which means that environmental degradation will first increase as per capita income increases but then will decrease after reaching certain level (i.e., the inflexion point) as per capita income continues to growth. This implies that economic growth will eventually redress the environmental impacts of the early stages of economic development. There are also many studies on the relationship between China's economic growth and environmental quality. These studies focus on verifying whether regional EKC exists (Zhang, 1999; Wang et al., 2016), exploring the economic development stage when the inflexion point of the EKC curve occurs as well as its driving mechanisms such as policy and technology, and analyzing the functional mechanisms of economic growth for environmental quality (Wu et al., 2002; Li et al., 2013a, 2013b; Yao et al., 2016).

The second area is the factors that influence SO_2 discharge. Further decomposition of the EKC curve shows that the influences of SO_2 discharge are mainly originated from the economic activity, economic structure, technology and composition effect of the region in questions (Stern, 1998; Antweiler et al., 2001). The growth of economic activity would often lead to the consumption of considerable energy resources; while changes in industrial structure and technical advancements may reduce environmental pollution. For example, A. H. Cheng (2011) discovered that the drop in China's industrial SO_2 discharge (ISOD) intensity in the period 1998–2008 was mainly because of the enhancement of pollution treatment technology, and P.D. Zhang et al. (2012a, 2012b) drew the same conclusion. After a country has economically developed to a certain level, people's increasing demand for environmental quality, government's financial resources and management ability, and the formulations of more effective environmental regulations will help improve environmental quality (Walter and Ugelow, 1979).

The third area is the influence of SO_2 discharge on human health and the environment. SO_2 discharge will directly affect human health since it increases mortality due to respiratory diseases (Freudenthal et al., 1989; Xie et al., 2010) and cerebrovascular diseases (Liu et al., 2013). In addition, the acid rain formed from SO_2 discharge has many negative influences on the environment, including soil, forest, agriculture, and water bodies (Sandoy and Langaker, 2001; Wang et al., 2005; Wei et al., 2014).

Recent studies have analyzed the temporal and spatial variations of SO_2 in various regions or countries in the world. For example, studies in Europe (Denby et al., 2010), Dallas County in Texas (Zou et al., 2011) and East Tennessee (Myles et al., 2009) in the USA; Istanbul (Tayanc, 2000) and Balikesir in Turkey (Tecer and Tagil, 2013); Patras in Greece (Yannopoulos, 2007); Hamilton at the western tip of Lake Ontario (Kanaroglou et al., 2013) in Canada; the Yangtze River Delta (Huang et al., 2011) and Pearl River Delta (Zhao et al., 2011) in China, and other regions (Wang and Chen, 2008; Cheng et al., 2013) have examined the distribution and variation of SO_2 with cross-sectional or time series data at fine spatial scales. Spatial analysis methods such as point pattern analysis and kriging spatial interpolation methods have also been to analyze SO_2 distribution (Wang and Chen, 2008; Zhao et al., 2011; Zhang et al., 2012a, 2012b). However, there is a relative lack of studies on the spatial characteristics of SO_2 discharge, especially the dependency and heterogeneity of SO_2 spatial distribution. Moreover, due to the different industrial land supply, economic development levels, degree of industrialization and SO_2 treatment technology in various cities in China, there are great spatial differences among different cities in the control of SO_2 discharge and air quality.

Spatial analysis is an important method for the quantitative study of various problems involving spatial relations in the natural, economic and social domains. It also offers an effective means for analyzing complex spatial patterns. This study analyzes the spatiotemporal variations of industrial SO_2 discharge (ISOD) amount and intensity with spatial autocorrelation modeling. It explores the driving forces of ISOD in China from 2001 to 2014 using spatial regression modeling. The study found that during this period ISOD amount increased first and then decreased, and ISOD intensity witnessed a fluctuating drop. Both ISOD amount and intensity had a more and more remarkable clustered spatial pattern. The study observed that land use and environmental policy had significant influences on ISOD in China. However, economic activity did not have a major influence on ISOD. These results provide important guidelines for and will inform future land use policies and environmental protection policies.

2. Data and methods

2.1. Data

In this study, cities at the municipal level are used as the spatial units for examining ISOD. The study period is from 2001 to 2014. Administrative divisions at the municipal level remained unchanged from 2004 to 2010 in China, and were readjusted slightly in other years. To ensure comparability of the results between different years, administrative units in years outside the 2004–2010 period are combined or decomposed to match the administrative units of the 287 municipal-level cities in 2010. Note that data for most of the cities in Xinjiang autonomous region, Tibet autonomous region,