# Spatiotemporal Distribution, Trans Regional Transmission and Causes of Air Pollution

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***Abstract***

*The survey region are important node cities in the North-South transmission channel of air pollution. Based on the long-term monitoring data of PM2.5 and PM10 in the survey region, we analyzed the temporal and spatial distribution, trans regional transmission and causes of air pollution. We found that the PM2.5 concentration and PM10 concentration of the survey region were different in different space and similar in time trend from 2015 to 2019. The air pollution in winter was the most serious. The air pollution in summer was the lowest. The transfer direction of PM2.5 was relatively single and that of PM10 was more complex. PM2.5 transfer was mainly affected by the concentration difference of air pollutants in different cities. PM2.5 transfer was mainly from high concentration areas to significantly low concentration areas. PM10 transfer was mainly affected by regional topography and climate characteristics. The analysis of the causes of local air pollutants showed that the primary industry, the secondary industry and the tertiary industry all contributed PM2.5. PM10 mainly came from the primary industry and the tertiary industry. Local governments not only need to control air pollution from the source but also need to coordinate across provinces. This paper used Econometrics and statistics models to analyze the cross regional transfer and provided a new reference method.*

***Keywords:*** *Air pollution, spatiotemporal distribution, trans regional transmission, PM2.5, PM10*

## I. Introduction

According to the statistics of the United Nations Environment Program, more than 6 billion people in the world and one third of children breathe polluted air every day. Their health and well-being are threatened. At the same time, according to the World Health Organization, 97% of cities with more than 100000 population in low and middle income countries do not meet safety standards of air quality. The percentage is 49% in high-income countries. About 7 million people die from exposure to tiny particles in polluted air each year. The tiny particles can penetrate into the lungs and cardiovascular system. Air pollution is an important risk factor for non communicable diseases. It is estimated that it accounts for one fourth (24%) of the total deaths from heart disease in adults, 25% of stroke, 43% of chronic obstructive pulmonary disease and 29% of lung cancer. Worryingly, more than 90% of deaths relate air pollution occur in low and middle income countries. These deaths are mainly in Asia and Africa, followed by low and middle income countries in the eastern Mediterranean region, Europe and the Americas.

In China, air pollution has become a growing concern of the whole society. According to the "Report on the State of the Ecology and Environment in China 2018" issued by the Ministry of ecology and environment of the people's Republic of China, the Ministry of ecology and environment of the people's Republic of China evaluated the comprehensive index of ambient air quality in 169 cities. Among the cities in the three provinces of Central China, only Xianning in Hubei Province ranked among the 20 cities with the best air quality in China. However, Zhengzhou, Jiaozuo and Xinxiang in Henan Province ranked among the 20 cities with the worst air quality in China. According to the "Report on the State of the Ecology and Environment in China 2019", Anyang, Jiaozuo, Xinxiang, Hebi and Zhengzhou of the five cities in Henan Province ranked among the 20

ISSN: 0010-8189

cities with the worst air quality in China. In 2019, none of the cities in the three provinces of Central China ranked among the 20 cities with the best air quality in China. Air pollution also brings acid rain. The central and eastern part of Hunan Province has become a serious area of acid rain in China. Beijing, Tianjin, Hebei, Yangtze River Delta, Pearl River Delta and other key regions are under the key monitoring of the Chinese government. Beijing, Tianjin, Hebei, Yangtze River Delta and other crucial regions have established regional air pollution prevention and control cooperation mechanisms. In contrast, Central China has not yet established a joint air pollution prevention and control mechanism. The three provinces in Central China are located in the North-South transmission channel of air pollutants in China. In addition to the air pollution produced in this region, it is easy to be affected by external input of air pollutants resulting in more serious pollution weather.

In recent years, some scholars have studied the spatiotemporal distribution of air pollution in some regions [1-4]. Other researchers have focused on the formation and transmission of air pollution [5-9]. In India, some Indian scholars have analyzed the seasonal and multi-year characteristics of air pollution over the Indian subcontinent by using the synchronous data of MODIS satellite sensors, considering the influence of monsoon factors [10]. Taking the dust storm in the Arabian Sea as an example, some Indian scholars have quantitatively studied the long-distance transport of wind dust to the Indian peninsula by using satellite and ground data. They have verified that the long-distance transport of dust generated by the storm will cause air pollution in remote areas [11].

There are also studies on the transport of air pollutants in Europe. Some scholars have studied the mass concentration, seasonal variation, chemical composition and element sources of PM10 in the urban area of Constantine, northeastern Algeria. The results show that the natural dust from the Sahara dust outbreak (SDOs) and resuspension dust is the main element source of PM10 in Constantine [12]. Some scholars have evaluated the participation of Sahara dust in PM10 events in four cities (Athens, Thessaloniki, Larisa and joanena) in the Greek mainland since 2012. The results showed that the vast majority of PM10 dust exceeding the standard came from direct dust intrusion from North Africa [13]. Some scholars have analyzed the air pollution of PM2.5 and PM10 measured in parallel for many years in two suburbs of Prague, Czech Republic. The results show that local sources contribute a lot to PM10, mainly in the Libu š site in Prague. However, regional pollution sources are also very important, and the impact of urban agglomeration pollution on PM10 can not be ignored [14].

There are similar studies in Africa and South America. Some scholars have studied the transport of PM10 over Cape Town during the period of high pollution. The results show that the transport of PM10 from the northwest coast of Southern Africa may be one of the reasons for the occurrence of PM10 in Cape Town [15]. Some scholars have analyzed the chemical characteristics of PM10 samples collected from cities and villages along the Caribbean coast. They have identified five main sources of PM10: Sahara intrusion, marine aerosol, combustion source, secondary aerosol, road traffic and cement plant [16].

To sum up, the existing literature is lack of research on air pollution in Central China and comprehensive consideration of various air pollution influencing factors (terrain conditions, industrial differences, pollution diffusion, etc.) to optimize the joint prevention and control mechanism of regional air pollution. Therefore, our research will include the spatiotemporal distribution of air pollution in Central China, the transfer of air pollutants in border cities and the analysis of the causes of air pollution, so that the joint prevention and control mechanism of regional air pollution will not only pay attention to the external transfer of air pollution but also take into account its own air pollution.

## II. Materials and Methods

2.1 Time and space

ISSN: 0010-8189

The joint prevention and control mechanism of regional air pollution is a long-term strategy, which needs to be established on the basis of long-term regional air condition analysis. In this study, we collected the concentration data of PM2.5 and PM10. The time span is from January 1, 2015 to December 31, 2019. The time span is totally 60 months. We also collected comprehensive data on regional air pollution, such as geographical characteristics, climate conditions, socio-economic development and seasonal characteristics of main crops cultivation and harvest in Central China. According to the spatial distribution, we choosed all the neighboring border cities in Central China. The neighboring border cities in Henan Province include Nanyang (NY), Zhumadian (ZMD) and Xinyang (XINY). The neighboring border cities in Hubei Province include Shiyan (SY), Xiangyang (XY), Suizhou (SZ), Xiaogan (XG), Huanggang (HG), Jingzhou (JZ), Xianning (XN) and Yichang (YC). The neighboring border cities in Hunan Province include Zhangjiajie (ZJJ), Changde (CD) and Yueyang (YY). There are 14 cities in all. The three provinces in Central China are shown in Fig. A.1.

## 2.2 Data sources

The concentration data of PM2.5 and PM10 are obtained from the data released by Ministry of Ecology and Environment the People's Republic of China (http://www.mee.gov.cn/hjzl/dqhj/cskqzlzkyb/). The comprehensive data of air pollution in Central China (geographical characteristics, climate conditions, socio-economic development, seasonal characteristics of cultivation and harvest of main crops) come from Henan statistical yearbook, Hubei statistical yearbook and Hunan statistical yearbook respectively compiled by Henan Provincial Bureau of statistics, Hubei Provincial Bureau of statistics and Hunan Provincial Bureau of statistics. The time span is from 2015 to 2019.

## 2.3 Method

Our analysis includes the following steps: the spatiotemporal distribution of air pollution, the trans regional transmission of air pollution and the analysis of the causes of air pollution.

According to the climate characteristics, we divided one year into four seasons. Spring is from March to May. Summer is from June to August. Autumn is from September to November. Winter is from December to February. Then, we calculated the average concentrations of pollutants in different seasons in different cities. Whether the average concentrations exceed the standard refers to ambient air quality standard of the Chinese government's standard (gb3095-2012). In accordance with the evaluation of ambient air quality standard (gb3095-2012), API 0-50 belongs to excellent air quality. 51-100 belongs to good air quality. 101-200 belongs to light air quality pollution. 201-300 belongs to moderate air quality pollution. More than 300 belongs to severe air quality pollution. The secondary standard of annual average value of fine particulate matter (PM2.5) is 35μg / m3. The secondary standard of daily average value is 75μg / m3. The secondary standard of annual average value of PM10 is 70μg / m3. The secondary standard of daily average value is 150μg / m3.

Based on the data of PM2.5 and PM10 concentrations in border cities in Central China, we calculated the monthly, seasonal and annual average concentrations of PM2.5 and PM10 in each city at first. Then we analyzed the spatiotemporal distribution of PM2.5 and PM10 concentrations in border cities of Central China. We also analyzed the the most serious month, season and year of air pollution.

In the next step, based on the monthly data of pollutant concentration in border cities of Central China, we carried out cluster analysis to explore the current situation of cross regional transfer of pollutants. The cluster analysis method adopted hierarchical clustering method. The distance between variables was measured by Pearson correlation coefficient. Cluster analysis was implemented by SPSS.

ISSN: 0010-8189

After that, we used Eviews software to do unit root test and Granger causality test on the pollutant concentration of border cities in Central China to see whether PM2.5 and PM10 are transmitted between border cities in Central China.

## III. Results

### 3.1 Spatiotemporal distribution

The statistical data of PM2.5 annual average concentration of 14 cities in Central China from 2015 to 2019 are shown in Table 1. In 2015, Changde had the lowest annual average concentration of PM2.5, while Xiangyang had the highest annual average concentration of PM2.5. In 2016, Xiaogan had the lowest annual average concentration of PM2.5, while Zhumadian had the highest annual average concentration of PM2.5. In 2017, Zhangjiajie had the lowest annual average concentration of PM2.5, while Xiangyang had the highest annual average concentration of PM2.5. In 2018, Xianning had the lowest annual average concentration of PM2.5, and Nanyang had the highest annual average concentration of PM2.5. In 2019, Zhangjiajie has the lowest annual average concentration of PM2.5, while Nanyang has the highest annual average concentration of PM2.5. From north to south, especially in 2015 and 2016, the annual average concentration of PM2.5 in Henan Province was higher. The annual average concentration of PM2.5 in Hubei Province was moderate. The annual average concentration of PM2.5 in Hunan Province was the lowest. From 2015 to 2018, the annual average concentration of PM2.5 in 14 cities decreased as a whole. In 2019, except Suizhou and Zhangjiajie, the annual average concentration of PM2.5 in other cities rebounded slightly. Except Zhangjiajie and Xianning, the annual average concentration of PM2.5 in other 12 cities in Central China exceeded the national secondary standard.

Table 1: Annual average concentration of PM2.5 in 14 cities in Central China (μg / m3)

| City | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|
| Nanyang | 74 | 61 | 47 | 54 | 60 |
| Zhumadian | 74 | 67 | 47 | 51 | 52 |
| Xinyang | 70 | 58 | 46 | 47 | 48 |
| Shiyan | 54 | 51 | 45 | 39 | 40 |
| Xiangyang | 77 | 64 | 67 | 54 | 60 |
| Suizhou | 66 | 56 | 51 | 42 | 42 |
| Xiaogan | 72 | 45 | 49 | 41 | 44 |
| Huanggang | 59 | 51 | 49 | 39 | 41 |
| Yichang | 70 | 62 | 58 | 49 | 52 |
| Jingzhou | 70 | 60 | 56 | 45 | 46 |
| Xianning | 55 | 48 | 48 | 34 | 36 |
| Zhangjiajie | 51 | 48 | 42 | 30 | 30 |
| Changde | 49 | 56 | 53 | 41 | 48 |
| Yueyang | 53 | 49 | 49 | 42 | 44 |

The statistical data of PM2.5 seasonal average concentration of 14 cities in Central China from 2015 to 2019 are shown in Table 2. From the seasonal point of view, the seasonal average concentration of PM2.5 was the lowest in summer and higher in autumn. It reached the peak in winter and decreased in spring. The seasonal average concentration of PM2.5 in each city in spring was close to that in autumn. In spring, Xiangyang was the city with the highest PM2.5 concentration, while Zhangjiajie was the city with the lowest PM2.5 concentration. In summer, Nanyang was the city with the highest PM2.5 concentration and Zhangjiajie was the city with the lowest PM2.5 concentration. In autumn, Xiangyang was the city with the highest PM2.5 concentration and Zhangjiajie was the city with the lowest PM2.5 concentration. In winter, Xiangyang was the city with the highest PM2.5 concentration. Meanwhile, Xianning was the city with the lowest PM2.5 concentration. From north to south, the seasonal average concentration of PM2.5 in cities of Henan Province was generally higher. The seasonal average concentration of PM2.5 in cities of Hubei Province was in the middle and that of Hunan Province was the lowest.

Table 2: Seasonal average concentration of PM2.5 in 14 cities in Central China (μg / m3)

| City | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| Nanyang | 49 | 35 | 48 | 104 |
| Zhumadian | 52 | 34 | 54 | 94 |
| Xinyang | 49 | 30 | 46 | 89 |
| Shiyan | 42 | 31 | 38 | 71 |
| Xiangyang | 53 | 33 | 56 | 117 |
| Suizhou | 46 | 30 | 43 | 87 |
| Xiaogan | 46 | 28 | 46 | 80 |
| Huanggang | 47 | 30 | 40 | 73 |
| Yichang | 51 | 29 | 45 | 108 |
| Jingzhou | 48 | 33 | 50 | 91 |
| Xianning | 40 | 27 | 40 | 69 |
| Zhangjiajie | 35 | 22 | 34 | 70 |
| Changde | 43 | 29 | 45 | 80 |
| Yueyang | 43 | 30 | 46 | 70 |

The statistical data of PM10 annual average concentration of 14 cities in Central China from 2015 to 2019 are shown in Table 3. In 2015, Zhangjiajie had the lowest annual average concentration of PM10 and Nanyang had the highest annual average concentration of PM10. In 2016, Yueyang had the lowest annual average concentration of PM10, while Zhumadian had the highest annual average concentration of PM10. In 2017, Shiyan had the lowest annual average concentration of PM10, while Xiangyang and Jingzhou had the highest annual average concentration of PM10. In 2018, Xianning had the lowest annual average concentration of PM10 and Nanyang had the highest annual average concentration of PM10. In 2019, Zhangjiajie had the lowest annual average concentration of PM10 and Nanyang had the highest annual average concentration of PM10. From north to south, the average concentration of PM10 in cities of Henan Province was the generally highest. Hubei Province was in the middle and Hunan Province was the lowest. From 2015 to 2018, the overall trend of PM10 average concentration in 14 cities continued to decline and rebounded slightly in 2019. In 2015 and 2016, the annual average concentration of PM10 in all major cities exceeded the national secondary standard of China. In 2017, 2018 and 2019, some cities in Hubei and Hunan could meet the national secondary standard of China and the annual average concentration of PM10 ranged from 51μg / m3 to 137μg / m3.

Table 3: Annual average concentration of PM10 in 14 cities in Central China (μg / m3)

| City | 2015 | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|
| Nanyang | 137 | 117 | 86 | 86 | 95 |
| Zhumadian | 126 | 120 | 83 | 85 | 88 |
| Xinyang | 112 | 96 | 76 | 77 | 77 |

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|---|---|---|---|---|---|
| Shiyan | 87 | 82 | 64 | 64 | 69 |
| Xiangyang | 106 | 95 | 94 | 79 | 88 |
| Suizhou | 103 | 88 | 78 | 68 | 70 |
| Xiaogan | 110 | 78 | 80 | 66 | 75 |
| Huanggang | 86 | 76 | 83 | 69 | 74 |
| Yichang | 108 | 99 | 91 | 71 | 76 |
| Jingzhou | 109 | 100 | 94 | 79 | 83 |
| Xianning | 89 | 80 | 69 | 51 | 59 |
| Zhangjiajie | 78 | 75 | 71 | 54 | 51 |
| Changde | 81 | 83 | 79 | 58 | 60 |
| Yueyang | 90 | 73 | 73 | 67 | 68 |

The seasonal average concentrations of PM10 in 14 cities in Central China from 2015 to 2019 are shown in Table 4. From the seasonal point of view, the average concentration of PM10 in summer was the lowest. The seasonal average concentrations of PM10 in 14 cities in Central China from 2015 to 2019 rised in autumn and reached the peak in winter. Then it decreased in spring. The average concentration of PM10 in spring was slightly higher than that in autumn in most cities. In spring and summer, Nanyang city had the highest PM10 concentration and Zhangjiajie City had the lowest PM10 concentration. In autumn, Zhumadian was the city with the highest PM10 concentration, while Zhangjiajie was the city with the lowest PM10 concentration. In winter, Nanyang was the city with the highest PM10 concentration and Xianning was the city with the lowest PM10 concentration. From north to south, the seasonal average concentration of PM10 in cities of Henan Province was generally higher. The seasonal average concentration of PM10 in cities of Hubei Province was in the middle and that of Hunan Province was the lowest.

Table 4: Seasonal average concentrations of PM10 in 14 cities in Central China (μg / m3)

| City | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| Nanyang | 104 | 66 | 88 | 158 |
| Zhumadian | 100 | 66 | 95 | 141 |
| Xinyang | 86 | 53 | 78 | 134 |
| Shiyan | 76 | 50 | 61 | 105 |
| Xiangyang | 89 | 59 | 83 | 138 |
| Suizhou | 81 | 47 | 70 | 128 |
| Xiaogan | 81 | 49 | 76 | 121 |
| Huanggang | 81 | 53 | 69 | 107 |
| Yichang | 88 | 56 | 74 | 138 |
| Jingzhou | 87 | 57 | 88 | 141 |
| Xianning | 70 | 47 | 64 | 97 |
| Zhangjiajie | 63 | 42 | 56 | 102 |
| Changde | 71 | 46 | 68 | 104 |
| Yueyang | 73 | 47 | 70 | 106 |

3.2 PM2.5 Cross regional transmission analysis

ISSN: 0010-8189

Because there were many cities, we divided the neighboring cities into two groups for the accuracy of cluster analysis. One group was neighboring cities of Henan and Hubei (Nanyang, Zhumadian, Xinyang, Shiyan, Xiangyang, Suizhou, Xiaogan, Huanggang). The other group was neighboring cities of Hubei and Hunan (Jingzhou, Xianning, Yichang, Zhangjiajie, Changde, Yueyang). Then we did cluster analysis respectively. According to the PM2.5 monthly average concentration data from 2015 to 2019, the hierarchical clustering method based on Pearson correlation was used. We used SPSS software for cluster analysis.

The eight neighboring cities in Henan and Hubei were generally divided into two categories, A1 (Nanyang, Zhumadian, Xinyang, Shiyan, Xiangyang) and A2 (Suizhou, Xiaogan, Huanggang). A1 included two sub categories, A11 (Nanyang, Zhumadian, Xinyang) and A12 (Shiyan, Xiangyang).

The six neighboring cities in Hubei and Hunan were generally divided into two categories, B1 (Jingzhou, Xianning, Zhangjiajie, Yichang) and B2 (Changde, Yueyang). B1 included two sub categories, B11 (Jingzhou, Xianning, Zhangjiajie) and B12 (Yichang).

Combined with the geographical location of the three provinces, we used Granger causality test to analyze the PM2.5 transmission between Henan and Hubei, Hubei and Hunan respectively according to the results of cluster analysis.

We used the PM2.5 concentration variables of border cities in neighboring provinces for unit root test and found that some variables had unit root, which was not a stationary series. In order to make the Granger test effective, we carried out the first-order difference for each time series. Then we implemented Granger causality test. We determined the optimal lag order according to AIC criterion. The test results are shown in Table A.1 and Table A.2. At the same time, we also draw the test results into a graph and used the arrow line to represent the trans regional transmission of PM2.5 in the border cities of the three provinces in Central China. These are shown in Fig. 1.

The Granger causality test results of PM2.5 in Henan and Hubei border cities are as follows. At 95% confidence level, Nanyang was the Granger cause of PM2.5 in Shiyan and Huanggang. Nanyang was not the Granger cause of PM2.5 in Xiangyang, Suizhou and Xiaogan. Shiyan, Xiangyang, Suizhou, Xiaogan and Huanggang were not the Granger cause of PM2.5 in Nanyang. Zhumadian was the PM2.5 Granger cause of Shiyan, Suizhou and Huanggang. Zhumadian was not the PM2.5 Granger cause of Xiangyang and Xiaogan and Shiyan. Xiangyang, Suizhou, Xiaogan and Huanggang were not the PM2.5 Granger cause of Zhumadian. Xinyang was the PM2.5 Granger cause of Shiyan, Xiangyang and Huanggang. Xinyang was not the PM2.5 Granger cause of Suizhou and Xiaogan. Shiyan, Xiangyang, Suizhou, Xiaogan and Huanggang were not the PM2.5 Granger cause of Xinyang. In general, PM2.5 was mainly transferred from border cities in Henan Province to border cities in Hubei Province.

The Granger causality test results of PM2.5 in Hubei and Hunan border cities are as follows. At the 95% confidence level, Yichang was not the Granger cause of PM2.5 in Zhangjiajie, Changde and Yueyang. Zhangjiajie, Changde and Yueyang were not the Granger cause of PM2.5 in Yichang. Jingzhou was the Granger cause of PM2.5 in Zhangjiajie and Changde. Jingzhou was not the Granger cause of PM2.5 in Yueyang. Zhangjiajie, Changde and Yueyang were not the Granger cause of PM2.5 in Jingzhou. Xianning was the Granger cause of PM2.5 in Zhangjiajie. Xianning was not the Granger cause of PM2.5 in Changde and Yueyang. Zhangjiajie, Changde and Yueyang were not the Granger cause of PM2.5 in Xianning. Generally speaking, PM2.5 was mainly transferred from border cities in Hubei Province to border cities in Hunan Province.

ISSN: 0010-8189

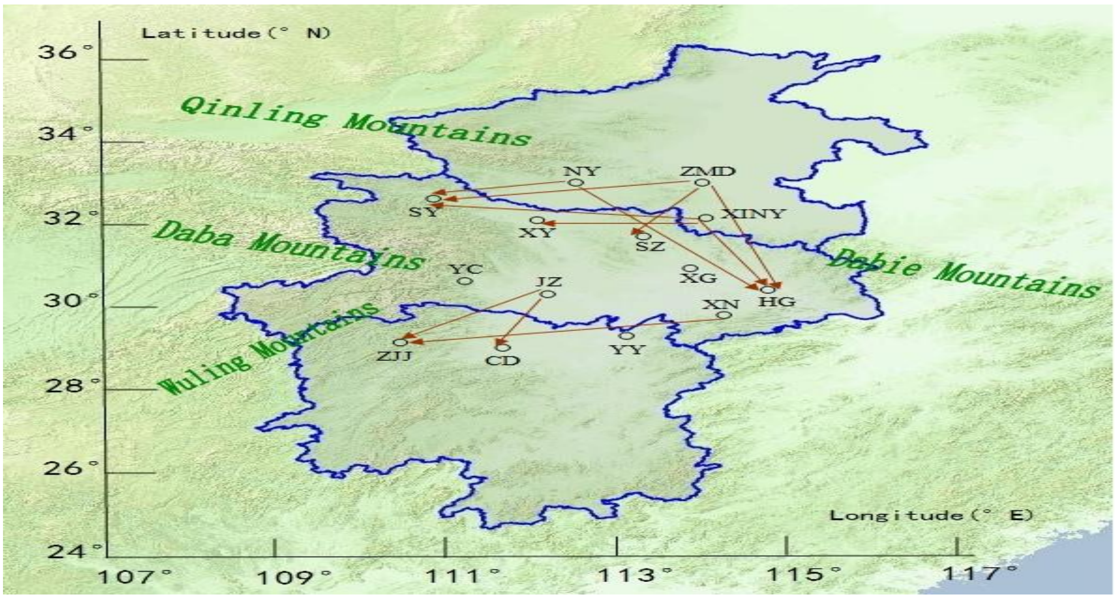


*Fig. 1: PM2.5 cross regional transmission(Nanyang(NY), Zhumadian(ZMD), Xinyang(XINY), Shiyan(SY), Xiangyang(XY), Suizhou(SZ), Xiaogan(XG), Huanggang(HG), Jingzhou(JZ), Xianning(XN), Yichang(YC),Zhangjiajie(ZJJ), Changde(CD), Yueyang(YY)).*

3.3 PM10 cross regional transmission analysis

According to the average concentration data of PM10 from 2015 to 2019, the hierarchical clustering method based on Pearson correlation was used. We used SPSS software for cluster analysis.

The eight neighboring cities in Henan and Hubei were generally divided into two categories, A1 (Nanyang, Zhumadian, Xinyang, Shiyan, Xiangyang) and A2 (Suizhou, Xiaogan, Huanggang). A1 included two sub categories, A11 (Nanyang, Zhumadian, Xinyang, Shiyan) and A12 (Xiangyang).

The six neighboring cities in Hubei and Hunan were generally divided into two categories, B1 (Yichang, Jingzhou, Zhangjiajie, Yueyang) and B2 (Xianning, Changde). B1 included two subclasses, B11 (Jingzhou, Yueyang) and B12 (Yichang, Zhangjiajie).

According to the results of cluster analysis, we used Granger causality test to analyze the PM10 transmission between Henan and Hubei, Hubei and Hunan respectively, combined with the geographical location of the three provinces.

We used the PM10 concentration variables of border cities in neighboring provinces for unit root test. We found that some variables had unit root, which was not a stationary series. In order to make the Granger test effective, we carried out the first-order difference for each time series and then implemented the Granger causality test. We determined the optimal lag order according to AIC criterion. The test results are shown in Table A.3 and Table A.4. At the same time, we also drew the test results into a graph and used the arrow line to represent the trans regional transmission of PM10 in the border cities of the three provinces in Central China. These are shown in Fig. 2.

The Granger causality test results of PM10 in border cities of Henan and Hubei are as follows. At the 95% confidence level, Nanyang was not the Granger cause of PM10 in Shiyan, Xiangyang, Suizhou, Xiaogan and Huanggang. Shiyan, Xiangyang, Suizhou, Xiaogan and Huanggang were not the Granger cause of PM10 in Nanyang. Zhumadian was not the Granger cause of PM10 in Shiyan, Xiangyang, Suizhou, Xiaogan and

ISSN: 0010-8189

Huanggang. Shiyan, Xiangyang, Suizhou, Xiaogan and Huanggang were not the Granger cause of PM10 in Zhumadian. Xinyang was the Granger cause of PM10 in Shiyan, Xiangyang and Huanggang. Xinyang was not the Granger cause of PM10 in Suizhou and Xiaogan. Shiyan, Xiangyang, Suizhou, Xiaogan and Huanggang were not the Granger cause of PM10 in Xinyang. Generally speaking, PM10 was mainly transferred from border cities in Henan Province to border cities in Hubei Province.

The Granger causality test results of PM10 in border cities of Hubei and Hunan are as follows. At the 95% confidence level, Yichang was not the Granger cause of PM10 in Zhangjiajie, Changde and Yueyang. Zhangjiajie and Yueyang were the Granger cause of PM10 in Yichang. Changde was not the Granger cause of PM10 in Yichang. Jingzhou was the Granger cause of PM10 in Zhangjiajie and Changde. Jingzhou was not the Granger cause of PM10 in Yueyang. Zhangjiajie, Changde and Yueyang were not the Granger cause of PM10 in Jingzhou. Xianning was not the Granger cause of PM10 in Zhangjiajie, Changde and Yueyang. Zhangjiajie, Changde and Yueyang were not the Granger cause of PM10 in Xianning. In a few words, PM10 was transmitted to each other in the border cities of Hubei Province and Hunan Province.

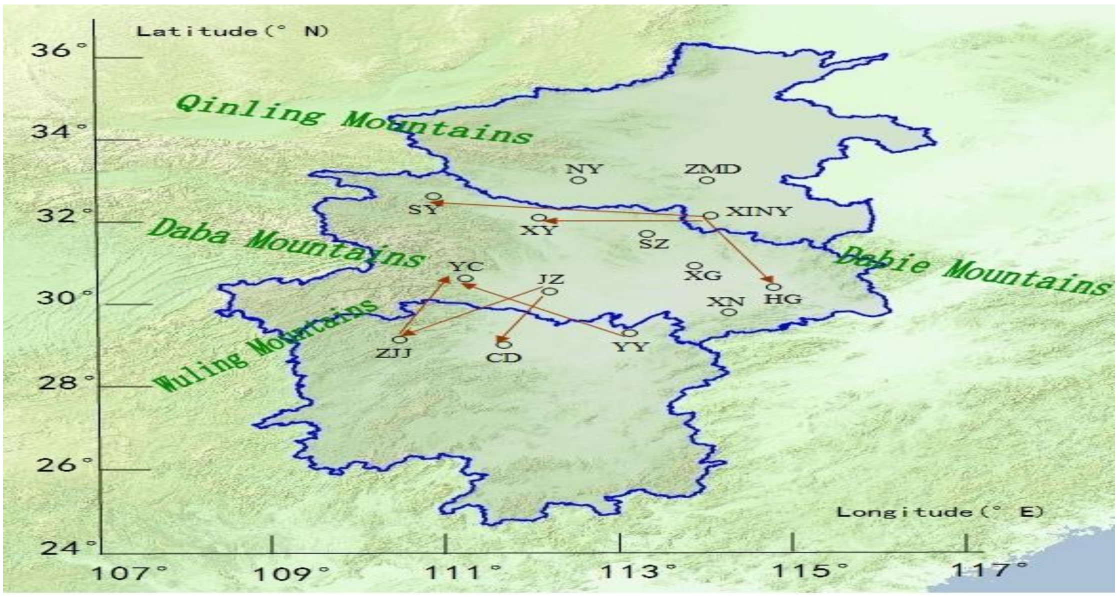


*Fig. 2: PM10 cross regional transmission(Nanyang(NY), Zhumadian(ZMD), Xinyang(XINY), Shiyan(SY), Xiangyang(XY), Suizhou(SZ), Xiaogan(XG), Huanggang(HG), Jingzhou(JZ), Xianning(XN), Yichang(YC),Zhangjiajie(ZJJ), Changde(CD), Yueyang(YY)).*

3.4 Causes of Air Pollutant Transfer

The concentration difference of air pollutants in neighboring cities is the important factor affecting the trans regional transfer of air pollutants. We conducted paired sample t-test on PM2.5 monthly average concentration of each city. The results are shown from Table 5 to table 6. We found that there was no Granger causality between the PM2.5 concentrations in different cities if there was no significant difference in PM2.5 monthly average concentration among cities. That is, there is no long-term transfer of pollutants such as Xinyang and Suizhou Generally. PM2.5 is transferred from cities with high monthly average concentration to cities with low monthly average concentration. At the same time, we conducted paired sample t-test on the average concentration of PM10 in each city. The results are shown in Table 7 and table 8. We found that we find that the Granger causality is little affected by the difference of PM10 monthly average concentration among cities. The transmission direction of PM10 was more easily affected by regional topography and climate characteristics. For example, the monthly average concentration of PM10 in Yichang was higher than that in Zhangjiajie and

Changde, but it was affected by Zhangjiajie and Changde. In terms of the number of paired cities, PM2.5 was more prone to cross regional transfer than PM10.

Table 5: Paired sample t-test on PM2.5 monthly average concentration of cities in Henan province and Hubei province.

| Pair group | City | T | Significance (two tailed) |
|---|---|---|---|
| Pair group 1 | Nanyang - Shiyan | 6.606 | .000 |
| Pair group 2 | Nanyang - Xiangyang | -3.175 | .002 |
| Pair group 3 | Nanyang - Suizhou | 4.302 | .000 |
| Pair group 4 | Nanyang - Xiaogan | 4.132 | .000 |
| Pair group 5 | Nanyang - Huanggang | 4.867 | .000 |
| Pair group 6 | Zhumadian - Shiyan | 7.506 | .000 |
| Pair group 7 | Zhumadian - Xiangyang | -2.935 | .005 |
| Pair group 8 | Zhumadian - Suizhou | 4.450 | .000 |
| Pair group 9 | Zhumadian - Xiaogan | 4.349 | .000 |
| Pair group 10 | Zhumadian - Huanggang | 5.288 | .000 |
| Pair group 11 | Xinyang - Shiyan | 5.145 | .000 |
| Pair group 12 | Xinyang - Xiangyang | -5.594 | .000 |
| Pair group 13 | Xinyang - Suizhou | 1.837 | .071 |
| Pair group 14 | Xinyang - Xiaogan | 2.266 | .027 |
| Pair group 15 | Xinyang - Huanggang | 3.553 | .001 |

Table 6: Paired sample t-test on PM2.5 monthly average concentration of cities in Hubei province and Hunan province.

| Pair group | City | T | Significance (two tailed) |
|---|---|---|---|
| Pair group 1 | Yichang - Zhangjiajie | 8.496 | .000 |
| Pair group 2 | Yichang - Changde | 3.990 | .000 |
| Pair group 3 | Yichang - Yueyang | 4.142 | .000 |
| Pair group 4 | Jingzhou - Zhangjiajie | 16.455 | .000 |
| Pair group 5 | Jingzhou - Changde | 4.353 | .000 |
| Pair group 6 | Jingzhou - Yueyang | 5.655 | .000 |
| Pair group 7 | Xianning - Zhangjiajie | 4.829 | .000 |
| Pair group 8 | Xianning - Changde | -4.014 | .000 |
| Pair group 9 | Xianning - Yueyang | -3.406 | .001 |

Table 7: Paired sample t-test on PM10 monthly average concentration of cities in Henan province and Hubei province.

| Pair group | City | T | Significance (two tailed) |
|---|---|---|---|
| Pair group 1 | Nanyang - Shiyan | 11.712 | .000 |
| Pair group 2 | Nanyang - Xiangyang | 5.094 | .000 |
| Pair group 3 | Nanyang - Suizhou | 9.111 | .000 |

| | | | |
|---|---|---|---|
| Pair group 4 | Nanyang - Xiaogan | 7.867 | .000 |
| Pair group 5 | Nanyang - Huanggang | 7.291 | .000 |
| Pair group 6 | Zhumadian - Shiyan | 11.924 | .000 |
| Pair group 7 | Zhumadian - Xiangyang | 3.123 | .003 |
| Pair group 8 | Zhumadian - Suizhou | 7.075 | .000 |
| Pair group 9 | Zhumadian - Xiaogan | 6.603 | .000 |
| Pair group 10 | Zhumadian - Huanggang | 7.078 | .000 |
| Pair group 11 | Xinyang - Shiyan | 7.545 | .000 |
| Pair group 12 | Xinyang - Xiangyang | -2.509 | .015 |
| Pair group 13 | Xinyang - Suizhou | 3.281 | .002 |
| Pair group 14 | Xinyang - Xiaogan | 2.768 | .008 |
| Pair group 15 | Xinyang - Huanggang | 3.777 | .000 |

Table 8: Paired sample t-test on PM10 monthly average concentration of cities in Hubei province and Hunan province.

| Pair group | City | T | Significance (two tailed) |
|---|---|---|---|
| Pair group 1 | Yichang - Zhangjiajie | 11.211 | .000 |
| Pair group 2 | Yichang - Changde | 6.016 | .000 |
| Pair group 3 | Yichang - Yueyang | 5.910 | .000 |
| Pair group 4 | Jingzhou - Zhangjiajie | 14.608 | .000 |
| Pair group 5 | Jingzhou - Changde | 9.171 | .000 |
| Pair group 6 | Jingzhou - Yueyang | 10.017 | .000 |
| Pair group 7 | Xianning - Zhangjiajie | 2.240 | .029 |
| Pair group 8 | Xianning - Changde | -1.623 | .110 |
| Pair group 9 | Xianning - Yueyang | -2.981 | .004 |

Regional topography has a significant impact on air pollutant transfer. Mountains can form a local pollution transfer area. At the junction of Henan and Hubei, there are Qinling Mountains in northwest-to-southeast direction in the north of the western region that includes Shiyan and the west of Nanyang. Daba Mountains in northwest-to-southeast direction are in the south of the region. These mountains are conducive to the transmission of air pollutants from east to west. Shiyan is located in the west of Nanyang, Zhumadian and Xinyang. PM2.5 and PM10 are significantly affected by Nanyang, Zhumadian and Xinyang. That is a good example. At the junction of Henan and Hubei, the eastern region that includes Xinyang and Huanggang is blocked by Dabie Mountains in northwest-to-southeast direction. Because the Dabie Mountains are divided into many rhombic fault blocks by faults and the valley between the mountains is wide and open, the air pollutants are easily transported from north to south. Huanggang PM2.5 and PM10 are significantly affected by Nanyang, Zhumadian and Xinyang. At the junction of Hubei and Hunan, there are Wuling Mountains in the west of Hunan. Wuling Mountains are northeast southwest and in favor of the transfer of air pollutants from north to south. Zhangjiajie is located in the northwest of Hunan Province. Jingzhou is located in the northeast of Zhangjiajie. Jingzhou is mainly a plain area. In addition, the concentrations of PM2.5 and PM10 in Jingzhou are higher than those in Zhangjiajie. Therefore, PM2.5 and PM10 in Zhangjiajie are significantly affected by Jingzhou. The terrain of Changde is relatively flat. A large part of Changde is plain and hilly. Jingzhou in the north of Changde. Therefore, PM2.5 and PM10 of Changde are significantly affected by Jingzhou.

Climate characteristics can also affect the transfer of air pollutants. Henan province belongs to the temperate monsoon climate. Under the influence of the strong cold high pressure of Siberia continent, the winter wind prevails in winter. There are mainly northwest wind. The wind is strong. The weather is fine and cold. The rain and snow are rare. It is difficult for the air to be purified by rain and snow. On the one hand, it will help the air pollutants transmit from the north to the south. On the other hand, it will also help the air pollutants transmit from Henan Province to the adjacent Hubei Province. Hubei Province and Hunan Province belong to subtropical monsoon humid climate, which is caused by the difference of land and sea thermal properties. In winter, the mainland cools quickly. The temperature is low, forming a high pressure. The ocean cools slowly. The temperature is high, forming a low pressure. The wind blows from the mainland to the ocean, forming a winter monsoon with less rain. In summer, the temperature of the mainland increases rapidly and the temperature is high, forming a low pressure. Meanwhile, the temperature of the ocean increases slowly and the temperature is low, forming a high pressure. The wind blows from the ocean to the mainland, forming a summer monsoon and precipitation. Therefore, air pollutants in Hubei Province and Hunan Province transfer to each other.

## IV. Discussion

### 4.1 Analysis difference between cluster analysis and granger causality test

Clustering is a process of classifying data into different classes or clusters, so the objects in the same cluster have great similarity. Our clustering analysis used the monthly average concentration data of air pollutants. The corresponding analysis result was also the monthly cross regional transfer analysis of air pollutants. Granger causality test was to analyze the "causality" in the statistical sense of time series data. Our Granger causality test used the second-order lag in the analysis process. The corresponding analysis result was the quarterly cross regional transfer analysis of air pollutants. Therefore, the analysis results of the two methods will be different, but they also contain each other. For example, PM2.5 cluster analysis shows that Nanyang, Zhumadian, Xinyang, Shiyan and Xiangyang had higher similarity. PM2.5 Granger causality test also showed that Nanyang, Zhumadian, Xinyang, Shiyan and Xiangyang do have causality. However, Xiangyang is mainly affected by Xinyang and the degree of influence is weaker than Shiyan. Granger causality test gave us the theoretical support to give priority to the treatment of air pollutants trans regional transfer city.

### 4.2 Local sources of air pollutants in border cities of central China

The local air pollutants mainly came from various economic activities of the three industries, so we choosed several representative variables of the three industries. First, we chose grain production as the source of air pollutants in the primary industry. The primary industry includes agriculture, forestry, animal husbandry and fishery. Forest, animal husbandry and fishery produce little air pollutants. In agriculture, the process of grain production is more likely to produce air pollutants. Rice and wheat will produce a lot of straw after receiving. With the development of rural economy and society, the energy source of farmers' cooking and heating has changed from traditional straw to electric power, coal and petroleum products. After grain and oil crops are harvested, a large number of straws are burned on the spot. It results in a large number of air pollutants. Then, we used industrial added value to represent the source of air pollutants in the secondary industry. The secondary industry refers to mining industry (excluding mining professional and auxiliary activities), manufacturing industry (excluding metal products, machinery and equipment repair industry), power, heat, gas and water production and supply industry, and construction industry. The second industry generally produces air pollutants. Finally, we chose the turnover of goods to represent the source of air pollutants in the tertiary industry. The third industry, namely service industry, refers to other industries except the first industry and the second industry. In the tertiary industry, transportation is the main source of air pollutants. Road transportation, water transportation and air transportation all need to consume a lot of various kinds of fuel. Air pollutants will be formed in the combustion process. It will bring trans regional pollutant transfer.

We selected the data of PM2.5, PM10, industrial added value, grain production and cargo turnover in 2019 to conduct Pearson correlation analysis. The results are shown in Table 9. The results showed that PM2.5 was significantly correlated with industrial added value, grain output and goods turnover. The primary industry, the secondary industry and the tertiary industry all contributed to PM2.5. PM10 was significantly correlated with grain output and cargo turnover. PM10 was mainly contributed by the primary and tertiary industries.

Table 9: Correlation analysis of local PM2.5 and PM10 air pollution sources (** indicates the correlation coefficient with significance level of 0.01).

| | | Industry | Grain | Cargo |
|---|---|---|---|---|
| PM2.5 | Pearson correlation | .793** | .729** | .791** |
| | Significance (two tailed) | .001 | .003 | .001 |
| PM10 | Pearson correlation | .478 | .771** | .834** |
| | Significance (two tailed) | .084 | .001 | .000 |

**V. Conclusion**

Based on the spatiotemporal analysis of PM2.5 and PM10 average concentration data of border cities of three provinces in Central China from January 2015 to December 2019, we found that PM2.5 and PM10 concentrations of border cities of three provinces in Central China were different in different spaces and similar in time trend. Geographically, the concentrations of PM2.5 and PM10 in border cities of Henan Province were the highest. The concentrations of PM2.5 and PM10 in border cities of Hubei Province were in the middle. The concentrations of PM2.5 and PM10 in border cities of Hunan Province were the lowest. Seasonally, the seasonal mean concentrations of PM2.5 and PM10 were the lowest in summer and increased in autumn. The seasonal mean concentrations of PM2.5 and PM10 peaked in winter and began to decline in spring. From 2015 to 2019, the annual average concentrations of PM2.5 and PM10 in the border cities of the three provinces in Central China showed an overall downward trend.

Cluster analysis and Granger causality test showed that the transmission direction of PM2.5 was relatively single and the transmission direction of PM10 was more complex. Between the border cities of Henan Province and Hubei Province, PM2.5 was mainly transferred from Henan Province to Hubei Province. Between the border cities of Hubei Province and Hunan Province, PM2.5 was mainly transferred from Hubei Province to Hunan Province. In the boundary cities of Henan Province and Hubei Province, PM10 mainly passed from Henan Province to Hubei Province. In the boundary cities of Hubei Province and Hunan Province, PM10 passed from Hubei Province to Hunan Province. PM2.5 transfer was mainly affected by the concentration difference of air pollutants in different cities. PM2.5 was mainly transferred from high concentration areas to significantly low concentration areas. PM10 transfer was mainly affected by regional topography and climate characteristics. The concentration difference of air pollutants in different cities can not determine the transfer direction of PM10. The analysis of the causes of local air pollutants showed that the primary industry, the secondary industry and the tertiary industry all contributed PM2.5. PM10 mainly came from the primary industry and the tertiary industry.

The governments of the three provinces in Central China should control the cross regional spread of air pollutants in border cities. In winter, when the pollution is most serious, they can restrict private cars to single or even numbers and encourage people to take more public transport. In addition, the governments of the three provinces in Central China need to ban the burning of agricultural straw, strengthen the environmental control of high pollution industries and use higher standards of fuel. All the air pollution prevention and control actions

ISSN: 0010-8189

need to be carried out jointly by the three provincial governments in Central China. Otherwise the ideal effect will not be achieved.

**Acknowledgements**

This research was supported by the National Natural Science Foundation of China (grant numbers No. 71573119).

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ISSN: 0010-8189

**Appendices**

Table A.1: Granger causality test results of PM2.5 in border cities of Henan and Hubei

| Null Hypothesis | F-Statistic | Prob. |
|---|---|---|
| Shiyan does not Granger Cause Nanyang | 1.6584 | 0.2004 |
| Nanyang does not Granger Cause Shiyan | 10.4458 | 0.0002 |
| Xinyang does not Granger Cause Shiyan | 8.8081 | 0.0005 |
| Shiyan does not Granger Cause Xinyang | 0.4025 | 0.6707 |
| Zhumadian does not Granger Cause Shiyan | 6.0014 | 0.0045 |
| Shiyan does not Granger Cause Zhumadian | 0.4237 | 0.6569 |
| Xiangyang does not Granger Cause Nanyang | 0.9725 | 0.3849 |
| Nanyang does not Granger Cause Xiangyang | 2.9518 | 0.0611 |
| Xinyang does not Granger Cause Xiangyang | 3.6610 | 0.0325 |
| Xiangyang does not Granger Cause Xinyang | 0.8060 | 0.4521 |
| Zhumadian does not Granger Cause Xiangyang | 0.8688 | 0.4254 |
| Xiangyang does not Granger Cause Zhumadian | 0.5267 | 0.5936 |
| Suizhou does not Granger Cause Nanyang | 1.5432 | 0.2233 |
| Nanyang does not Granger Cause Suizhou | 2.0783 | 0.1354 |
| Xinyang does not Granger Cause Suizhou | 2.2020 | 0.1208 |
| Suizhou does not Granger Cause Xinyang | 0.9015 | 0.4122 |
| Zhumadian does not Granger Cause Suizhou | 3.5124 | 0.0371 |
| Suizhou does not Granger Cause Zhumadian | 1.4661 | 0.2402 |
| Xiaogan does not Granger Cause Nanyang | 1.5148 | 0.2294 |
| Nanyang does not Granger Cause Xiaogan | 0.7271 | 0.4881 |
| Xinyang does not Granger Cause Xiaogan | 0.9649 | 0.3878 |
| Xiaogan does not Granger Cause Xinyang | 0.7918 | 0.4584 |
| Zhumadian does not Granger Cause Xiaogan | 1.6724 | 0.1977 |
| Xiaogan does not Granger Cause Zhumadian | 0.9553 | 0.3913 |
| Nanyang does not Granger Cause Huanggang | 3.1843 | 0.0496 |
| Huanggang does not Granger Cause Nanyang | 0.9835 | 0.3808 |
| Xinyang does not Granger Cause Huanggang | 3.5079 | 0.0372 |
| Huanggang does not Granger Cause Xinyang | 0.3752 | 0.6890 |
| Zhumadian does not Granger Cause Huanggang | 5.9109 | 0.0049 |
| Huanggang does not Granger Cause Zhumadian | 0.5913 | 0.5573 |

Table A.2: Granger causality test results of PM2.5 in border cities of Hubei and Hunan

| Null Hypothesis | F-Statistic | Prob. |
|---|---|---|
| Yichang does not Granger Cause Changde | 1.4645 | 0.2406 |
| Changde does not Granger Cause Yichang | 1.0860 | 0.3451 |
| Zhangjiajie does not Granger Cause Yichang | 2.1342 | 0.1286 |
| Yichang does not Granger Cause Zhangjiajie | 3.0486 | 0.0560 |

ISSN: 0010-8189

| | | |
|---|---|---|
| Yueyang does not Granger Cause Yichang | 2.7157 | 0.0755 |
| Yichang does not Granger Cause Yueyang | 0.6854 | 0.5084 |
| Zhangjiajie does not Granger Cause Jingzhou | 0.3698 | 0.6927 |
| Jingzhou does not Granger Cause Zhangjiajie | 11.9749 | 0.0001 |
| Jingzhou does not Granger Cause Changde | 5.1458 | 0.0091 |
| Changde does not Granger Cause Jingzhou | 0.3251 | 0.7239 |
| Yueyang does not Granger Cause Jingzhou | 0.0271 | 0.9733 |
| Jingzhou does not Granger Cause Yueyang | 1.5488 | 0.2221 |
| Zhangjiajie does not Granger Cause Xianning | 0.8633 | 0.4277 |
| Xianning does not Granger Cause Zhangjiajie | 4.7564 | 0.0127 |
| Xianning does not Granger Cause Changde | 2.5200 | 0.0902 |
| Changde does not Granger Cause Xianning | 0.3531 | 0.7042 |
| Yueyang does not Granger Cause Xianning | 0.1270 | 0.8810 |
| Xianning does not Granger Cause Yueyang | 0.0900 | 0.9140 |

Table A.3: Granger causality test results of PM10 in border cities of Henan and Hubei

| Null Hypothesis: | F-Statistic | Prob. |
|---|---|---|
| Shiyan does not Granger Cause Nanyang | 0.6308 | 0.5362 |
| Nanyang does not Granger Cause Shiyan | 2.8997 | 0.0640 |
| Xinyang does not Granger Cause Shiyan | 5.4348 | 0.0072 |
| Shiyan does not Granger Cause Xinyang | 0.5303 | 0.5916 |
| Zhumadian does not Granger Cause Shiyan | 1.8361 | 0.1696 |
| Shiyan does not Granger Cause Zhumadian | 0.0074 | 0.9926 |
| Xiangyang does not Granger Cause Nanyang | 0.0915 | 0.9127 |
| Nanyang does not Granger Cause Xiangyang | 1.4934 | 0.2341 |
| Xinyang does not Granger Cause Xiangyang | 5.4367 | 0.0072 |
| Xiangyang does not Granger Cause Xinyang | 0.2429 | 0.7852 |
| Zhumadian does not Granger Cause Xiangyang | 0.3911 | 0.6783 |
| Xiangyang does not Granger Cause Zhumadian | 0.1672 | 0.8465 |
| Suizhou does not Granger Cause Nanyang | 1.4781 | 0.2375 |
| Nanyang does not Granger Cause Suizhou | 0.7032 | 0.4996 |
| Xinyang does not Granger Cause Suizhou | 1.8334 | 0.1701 |
| Suizhou does not Granger Cause Xinyang | 0.7005 | 0.5010 |
| Zhumadian does not Granger Cause Suizhou | 0.7652 | 0.4704 |
| Suizhou does not Granger Cause Zhumadian | 1.5476 | 0.2224 |
| Xiaogan does not Granger Cause Nanyang | 1.3558 | 0.2667 |
| Nanyang does not Granger Cause Xiaogan | 0.2795 | 0.7573 |
| Xinyang does not Granger Cause Xiaogan | 0.6739 | 0.5141 |
| Xiaogan does not Granger Cause Xinyang | 1.2382 | 0.2983 |
| Zhumadian does not Granger Cause Xiaogan | 0.0995 | 0.9055 |

ISSN: 0010-8189

| | | |
|---|---|---|
| Xiaogan does not Granger Cause Zhumadian | 0.8695 | 0.4252 |
| Nanyang does not Granger Cause Huanggang | 2.1678 | 0.1247 |
| Huanggang does not Granger Cause Nanyang | 0.1393 | 0.8703 |
| Xinyang does not Granger Cause Huanggang | 3.3683 | 0.0421 |
| Huanggang does not Granger Cause Xinyang | 0.1469 | 0.8638 |
| Zhumadian does not Granger Cause Huanggang | 2.0733 | 0.1360 |
| Huanggang does not Granger Cause Zhumadian | 0.2467 | 0.7823 |

Table A.4: Granger causality test results of PM10 in border cities of Hubei and Hunan

| Null Hypothesis | F-Statistic | Prob. |
|---|---|---|
| Yichang does not Granger Cause Changde | 0.3033 | 0.7397 |
| Changde does not Granger Cause Yichang | 1.9310 | 0.1553 |
| Zhangjiajie does not Granger Cause Yichang | 3.9160 | 0.0260 |
| Yichang does not Granger Cause Zhangjiajie | 0.9970 | 0.3759 |
| Yueyang does not Granger Cause Yichang | 5.2429 | 0.0084 |
| Yichang does not Granger Cause Yueyang | 2.1266 | 0.1295 |
| Zhangjiajie does not Granger Cause Jingzhou | 0.7144 | 0.4942 |
| Jingzhou does not Granger Cause Zhangjiajie | 7.2873 | 0.0016 |
| Jingzhou does not Granger Cause Changde | 4.7755 | 0.0125 |
| Changde does not Granger Cause Jingzhou | 0.2556 | 0.7754 |
| Yueyang does not Granger Cause Jingzhou | 0.0195 | 0.9807 |
| Jingzhou does not Granger Cause Yueyang | 0.4117 | 0.6647 |
| Zhangjiajie does not Granger Cause Xianning | 0.2854 | 0.7529 |
| Xianning does not Granger Cause Zhangjiajie | 0.6626 | 0.5198 |
| Xianning does not Granger Cause Changde | 2.7794 | 0.0713 |
| Changde does not Granger Cause Xianning | 0.0279 | 0.9725 |
| Yueyang does not Granger Cause Xianning | 0.3866 | 0.6813 |
| Xianning does not Granger Cause Yueyang | 0.8504 | 0.4331 |


*Fig. A.1: The three provinces in Central China*

ISSN: 0010-8189