Measurement of carbon emission efficiency of China's energy consumption and its spatial distribution pattern

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Abstract: Based on the data of eight kinds of energy consumption in each province from 2000 to 2016, the carbon emissions generated by energy consumption in each province are calculated, and the carbon emission efficiency of energy consumption is further calculated and its spatial distribution pattern is studied. The results show that the carbon emission efficiency of China's energy consumption has improved as a whole during the sample period, and the efficiency distribution exists in different regions. To some extent, there is weak positive spatial correlation, but the overall Moran I index shows that there is no significant spatial correlation in the sample as a whole.

1. Introduction
Based on the current situation of global warming, carbon emission and its efficiency have gradually become a hot issue. There are many sources and calculation methods of carbon emission, and there are many methods of efficiency evaluation, and the research on the characteristics of carbon emission efficiency has always been a hot issue. The main focus is on the calculation of carbon emissions and efficiency of energy consumption in each province of China, and on this basis, further analysis of its spatial pattern. Wang et al.[1] calculated the energy efficiency in different regions of China based on the improved non radial SBM model, it is found that although the energy efficiency of different regions is very different, there is a significant trend of convergence in statistical significance, which indicates that there may be spillover effect or contagion effect between regions due to the proximity of geographical location, leading to the convergence of carbon emission efficiency in the adjacent regions. Li et al.[2] found that the carbon emission efficiency of cities in the Yangtze River Delta economic belt has significant spatial aggregation. Khalid[3] and others found that there is a phenomenon of transfer from high-income countries to low-income countries in high pollution industries, and there is an international transfer of carbon emissions. The research of these scholars shows that there may be spatial correlation among industries, urban agglomerations, provinces and even international. In order to further study the carbon emission efficiency and provide the corresponding basis for improving the efficiency, we will start from the carbon emission generated by energy consumption, and explore whether its efficiency has similar phenomenon, as a useful supplement and expansion of the existing literature.

2. Model building

2.1 Calculation model of carbon emission
The calculation method of carbon emission is provided by IPCC (Intergovernmental Panel on climate change), which is calculated as follows:

\[ \text{carbon emission intensity} = \frac{\text{total carbon emission}}{\text{total energy consumption}} \]
\[ CE = \sum_{i=1}^{n} (CO_2) = \sum_{i=1}^{n} E_i \times NCV_i \times CEF_i \times \frac{44}{12} \quad (1) \]

In the formula: \( E \) —— Annual consumption (kg) of coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil and natural gas in each province; \( NCV \) —— Net calorific value of corresponding energy (kJ/kg); \( CEF \) —— Carbon emission factor (kg-CO₂/kg); \( COF \) —— Unit conversion factor of energy (dimensionless). All the above data can be obtained from the statistical yearbook over the years and the general principles for calculation of comprehensive energy consumption compiled by China.

2.2 Calculation of carbon emission efficiency

The carbon emission efficiency is calculated by using the SBM model which contains the undesirable output. It is a typical nonparametric estimation method. Compared with the typical parameter estimation SFA method, the advantage of this model is that it does not need a specific function form and takes into account the slack and unintended output variables, while the accuracy of the estimation results of the parameter method is closely related to the specific production function form. The selection and setting of specific indicators of SBM method are shown in Table 1.

| Table 1 efficiency measurement index |
|--------------------------------------|
| First level indicators | Secondary level indicators | Three level indicators |
| Input index | Capital investment \( K \) | Annual fixed capital investment by Region |
| | Labor input \( L \) | Permanent population of each region at the end of the year |
| Output index | Desirable Output | Annual GDP of each region |
| | undesirable output | Carbon emissions from energy use by Region |

2.3 Spatial correlation test

In order to test whether there is spatial correlation in carbon emission efficiency of energy use in China, the most common global Moran I index is used. The calculation method is as follows⁴:

\[ I = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}} \quad (2) \]

In the formula: \( w_{ij} \) —— Elements of spatial weight matrix \((i, j)\), corresponding to provinces \((i, j)\), space weight matrix is a matrix of order, if \( w \neq 0 \), it means that there is a spatial relationship between observation objects \( i \) and \( j \), otherwise, there is no spatial connection; \( S^2 \) —— Variance of samples; \( \sum_{j=1}^{n} \sum_{i=1}^{n} w_{ij} \) —— The sum of the elements of the spatial weight matrix. After standardizing the row of spatial weight matrix, the value of Moran is generally between -1 and 1. If the value is significantly greater than 0, it means that there is a significant positive spatial autocorrelation in the energy use carbon emission efficiency of each province; otherwise, it means that there is a significant negative spatial autocorrelation; if the value is close to 0, it means that the spatial distribution is random.

The spatial relationship between the elements \( i \) and \( j \) represented by coefficients \( w_{ij} \) in the spatial weight matrix. There are many methods to construct them. Generally speaking, they are divided into adjacent matrix and distance matrix. Among them, the adjacent matrix is a spatial weight matrix composed of 0 and 1 according to whether the regions \( i \) and \( j \) are adjacent or not. If the elements are adjacent, then \( w_{ij} = w_{ji} = 1 \). According to the different principle of adjacent, it can be divided into three kinds: rook, bishop and queen. The distance matrix can also be divided into many kinds according to the different definition of distance, such as geographic distance, geometric distance, economic distance,
etc. In his research, Li Ran\cite{5}, a scholar, found that the spatial weight matrix based on economic weight had more significant influence on the economic variables studied. In this paper, the economic distance weight matrix was also used to calculate the global Moran index $I$.

$$W_{ij} = \begin{cases} 
\frac{1}{Y_i - Y_j}, & i \neq j \\
0, & i = j 
\end{cases} \quad (3)$$

$$Y_j = \frac{1}{t_1 - t_0 + 1} \sum_{t=t_0}^{t_1} Y_{it}$$

Referring to the practice of Lin Guangping\cite{6} (2005), the specific calculation method of spatial weight is shown in formula (3), where $\bar{Y}_i$ is the average annual GDP of region $i$, where time $t_0 = 2000$, $t_1 = 2016$. When the GDP mean difference between regions $i$ and $j$ is smaller, the value of the weight matrix $W_{ij}$ will be larger. Compared with the 0-1 adjacent matrix, the spatial weight matrix here considers the economic differences between regions, which is more practical.

3. Result analysis

By using Jenks, the carbon emission efficiency of energy use in all provinces of China is naturally divided into four levels: low efficiency, medium low efficiency, medium high efficiency and high efficiency. Limited to space limitation, only the results of carbon emission efficiency grading of each province in 2000 and 2015 are shown here. The specific results are shown in Table 2.

| Efficiency level | 2000 | 2015 |
|------------------|------|------|
| high efficiency  | Beijing, Shanghai, Fujian, Guangdong, Hainan, Ningxia, Qinghai | Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Guangdong, Hainan, Ningxia, Qinghai |
| Medium and high efficiency | Heilongjiang, Liaoning, Tianjin, Shandong, Zhejiang, Jiangsu, Hunan, Chongqing | Shandong, Fujian, Hunan, Chongqing |
| Low efficiency   | Jilin, Hebei, Shanxi, Henan, Anhui, Yunnan, Guangxi, Xinjiang | Heilongjiang, Jilin, Liaoning, Henan, Hubei, Shaanxi, Sichuan, Guizhou, Guangxi, Yunnan, Xinjiang, Inner Mongolia |
| poor efficiency  | Inner Mongolia, Gansu, Shaanxi, Hubei, Jiangxi, Sichuan, Guizhou | Hebei, Shanxi, Anhui, Jiangxi, Gansu |

It can be found that from 2000 to 2015, the carbon emission efficiency of energy use in all provinces of China is distributed in patches. Specifically speaking, the carbon emission efficiency in the eastern coastal areas of China is basically in the two grades of high efficiency and medium efficiency. In 2000, the provincial administrative regions with high carbon emission efficiency in energy use were Qinghai, Ningxia, Beijing, Shanghai, Fujian, Guangdong and Hainan, and the provinces with medium and high efficiency were Heilongjiang, Liaoning, Shandong, Jiangsu and Zhejiang, Chongqing and Hunan; in 2005, compared with 2000, the provinces and cities in the high efficiency level added Tianjin. In the middle and high efficiency level, the number of provinces decreased to Liaoning and the number of new provinces increased to Guangxi; in 2010, Hunan, Jiangsu and Zhejiang changed from medium efficiency in 2005 to high efficiency, while Guangxi dropped out of the medium efficiency level; in 2015, Fujian and Hunan changed from high efficiency to medium efficiency, while Heilongjiang dropped out of the medium efficiency group.
From 2000 to 2016, the distribution results of carbon emission efficiency of each province over the years generally show that the carbon emission efficiency of energy use in China shows a certain geographical spatial clustering feature, and the carbon emission efficiency of the eastern region is generally higher, followed by that of the central and western regions; during the sample period, the classification results of carbon emission efficiency of energy consumption in China have not changed greatly. Moreover, the number of provinces with high and medium efficiency accounts for about one third of the total number, which has not changed greatly; the number of provinces in the low efficiency level has been reduced from 7 in 2000 to 5 in 2015, which shows that the carbon emission efficiency of energy use in China has improved during the sample statistics period.

| Particular year | Moran indexI | The value of Z | P-VALUE |
|-----------------|--------------|----------------|---------|
| 2000            | 0.073        | 1.122          | 0.131   |
| 2001            | 0.07         | 1.088          | 0.138   |
| 2002            | 0.069        | 1.08           | 0.14    |
| 2003            | 0.083        | 1.222          | 0.111   |
| 2004            | 0.07         | 1.089          | 0.138   |
| 2005            | 0.063        | 1.014          | 0.155   |
| 2006            | 0.066        | 1.046          | 0.148   |
| 2007            | 0.07         | 1.086          | 0.139   |
| 2008            | 0.105*       | 1.441          | 0.075   |
| 2009            | 0.113*       | 1.525          | 0.064   |
| 2010            | 0.132**      | 1.72           | 0.043   |
| 2011            | 0.148**      | 1.886          | 0.03    |
| 2012            | 0.16**       | 2.018          | 0.022   |
| 2013            | 0.151**      | 1.924          | 0.027   |
| 2014            | 0.134*       | 1.749          | 0.04    |
| 2015            | 0.125*       | 1.653          | 0.049   |
| 2016            | 0.114*       | 1.542          | 0.062   |

Note: *, **, * * * are significant at the significance level of 1%, 5% and 10%, respectively.

The results of calculating global Moran index $I$ using the standardized economic spatial weight matrix are shown in Table 3. The results show that the global Moran index $I$ values from 2000 to 2016 are all positive, but not significant at the level of 1%, and significant at the level of 5% in some years. This shows that to some extent, there is a weak positive spatial correlation in the efficiency of carbon emissions from energy use in China, but there is no high spatial correlation in the efficiency of carbon emissions from energy use during the sample period.

## 4. Conclusion

Using the consumption data of coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil and natural gas in each province from 2000 to 2016, combined with the carbon emission calculation model and the SBM model including the undesirable output, the carbon emission and its efficiency of energy use in each province over the years are calculated, and on this basis, the spatial distribution pattern of carbon emission efficiency is studied. The main conclusions are as follows: first, the spatial distribution of carbon emission efficiency of energy use in China shows a geographical clustering feature, except for Qinghai and Ningxia in the central and western regions, the overall carbon emission efficiency of the eastern coastal areas is generally high; secondly, in terms of efficiency change, the number of provinces with high and medium efficiency in the sample period accounts for about one-third of the total number, and no significant change has taken place; Third, the number of provinces in the low efficiency level has decreased from 7 in 2000 to 5 in 2015, which shows that the efficiency of carbon emission from
energy use in China has improved during the sample statistics period. Finally, the spatial correlation analysis shows that the efficiency of carbon emission from energy use in China has weak spatial positive correlation to some extent, but more is the result of spatial random distribution.

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