Chin. Geogra. Sci. 2009 19(2) 126–134
DOI: 10.1007/s11769-009-0126-9
www.springerlink.com

Spatio-temporal Analysis of Urban Spatial Interaction in Globalizing China —A Case Study of Beijing-Shanghai Corridor

WU Wenjie[1, 2], ZHANG Wenzhong[1], JIN Fengjun[1], DENG Yu[1, 2]
(*1.Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China; 2. Graduate University of the Chinese Academy of Sciences, Beijing 100049, China*)

Abstract: This paper aims to explore urban geography with a new perspective. Endowed with the urban geography connotations, an improved data field model is employed to integrate temporal dimension into spatial process of cities in a typical region in this article. Taking the Beijing-Shanghai corridor including 18 cities as an example, the authors chose the city centricity index (CCI) and the spatial data field model to analyze the evolution process and features of sub-region and urban spatial interaction in this corridor based on the data of 1991, 1996 and 2002. Through the analysis, we found that: 1) with the improvement of the urbanization level and the development of urban economy, the cities' CCI grew, the urban spatial radiative potential enhanced and the radiative range expanded gradually, which reflects the urban spatial interaction's intensity has been increasing greatly; 2) although the spatial interaction intensity among the cities and sub-regions in the Beijing-Shanghai corridor was growing constantly, the gap of the spatial interaction strength among different cities and sub-regions was widening, and the spatial division between the developed areas and the less developed areas were obvious; and 3) the intensity of the spatial interaction of Beijing, Shanghai and their urban agglomerations was far greater than that in small cities of other parts of the corridor, and it may have a strong drive force on the choice of spatial location of the economic activities.

Keywords: urban spatial interaction; data field; Beijing-Shanghai corridor; China

1 Introduction

Globalization has brought about profound structural changes not only in Chinese economy but also in the urban spatial interaction among Chinese cities (or regions). The growth and structural transformation of the urban spatial interactions have captured global attention. However, due to the complex nature of the subject matter, the changing inter-relationship between urban development and urban spatial interaction in Chinese cities can not be explained by a favorable model at a reasonable scale.

Despite that classical physics has achieved splendid results in many fields and has been introduced to Geography, it is not widely accepted in urban studies. The application of the physical idea to geographical phenomena was promoted by physicists (Wilson, 1970; James and Martin, 1981). Fortunately, from then on, cities, which used to appear in social physics, have caught physicists' attention, and some interesting discoveries on urban growth and development were made these years (Wilson, 1970; James and Martin, 1981; Batty and Longley, 1994; Makse et al., 1995; 1998; Zanette and Manrubia, 1997; Manrubia and Zanette, 1998; Chen and Zhou, 2004). As medium-sized phenomena and complex systems, cities are indeed the study objects coming between physics and geography. One of the typical subjects associating urban spatial interaction theories in geography with physics is the data field model, which can reflect the urban spatial interactions (Wilson, 1967; 1971; Alonso, 1978; Fotheringham, 1983; Wang and Ding, 1994; Xue and Yang, 2005; Li, 2001).

In China, one of the largest developing countries re-

Received date: 2008-11-05; accepted date: 2009-02-27
Foundation item: Under the auspices of Key Project of National Natural Science Foundation of China (No. 40635026), National Natural Science Foundation of China (No. 40701045)
Corresponding author: ZHANG Wenzhong. E-mail: zhangwz@igsnrr.ac.cn

cently re-integrated itself with the globalizing world, and there is a large body of literature focusing on the emergence of “urban growth” or “super urban agglomeration” in the country as a result of the intrusion of global forces (Kirkby, 1985; Pannell, 1990; Gaubatz, 1999). However, relatively little is understood about the fundamental processes of urban spatial interaction unfolding in China in the current era of globalization temporally and spatially. Although the Chinese cities are not so significant as such “world cities” as New York, Paris, and Tokyo in economy, their continued expansion has posed great challenges not only for the theoretical understanding of urban transformation in a transitional planned economy but also for planning and policy-making for the betterment of over one-fifth of humankind (Gaubatz, 1999; Ma, 2002; Pannell, 2002).

In Geography, corridor is a highly developed multimodel urban network, linking at least two large cities or urban agglomerations, which forms a spatial economic system eventually and plays an important role in the regional development (Whebell, 1969; Aljarad and Black, 1995). By an improved data field model propounded by giving its urban geography meanings, this study examines the urban spatial interaction within a typical area—Beijing-Shanghai Corridor in China. It is a most significant regional corridor with an urban economy undergoing profound structural and spatial changes in recent years as China continues to carry out its reforms and opening up programs. The purpose is to study the spatial and temporal process of urban spatial interaction as a consequence of the accelerated city’s economic & traffic development and its urbanization in a finer scale. Although the case can not be taken as representative of the general situation in the country, a detailed assessment of changes in urban spatial interaction over time and across space within a typical region can help generate important insights into the characteristics of urban spatial interaction in a transitional socialist economy in the era of marketization and globalization.

2 Study Area and Data

In this article, the Beijing-Shanghai Corridor including 18 Chinese cities was studied as an empirical analysis, which is one of the most developed regional corridors in China, as well as in East Asia.

The Beijing-Shanghai high speed railway is the main axis of the corridor, connecting the most developed urban agglomeration and regions such as the Jing-Jin (Beijing-Tianjin) Region, urban agglomeration in the Changjiang (Yangtze) River Delta, and other urban compact districts. There are 18 cities along the railway traffic line, including three important municipalities directly under the Central Government of China (Beijing, Tianjin and Shanghai), two provinces’ capital cities (Jinan and Nanjing) and other 13 major cities (each has a population of more than 1×10^6), which covered only 6.5% land area of the whole nation, but with 26.27% of the country's total population (National Bureau of Statistics of China, 2004). Thus, those 18 cities in the Beijing-Shanghai Corridor constitute a strong economic development axis (Fig. 1).

In our datasets, the statistical data of 18 cities were collected from the *Urban Statistical Yearbook of China* in 1991, 1996, 2000, 2006 (National Bureau of Statistics of China, 1992; 1997; 2001; 2007).

3 Methodology

3.1 Theoretical foundation

Physics research often involves the question of physical quantity which distributes in a certain spatial region, often referred to as "field", such as the gravitational field, electric field, etc. The attributes of the physical field are usually described as a space location (coordinates), called vector field or scalar field in physics. Potential-energy is a very important scalar field, and the potential-energy function is a function of particle location. In physics, it usually uses potential lines and potential surface to describe the potential-energy function in the spatial distribution, such as contour lines, isotherm, etc., and it is defined that each data object in the domain space are equivalent to one particle, which is surrounded by a certain field. Then any other data objects in this field will be affected, therefore, the entire domain space constitute a data field.

In order to describe the attribute of the data field, a scalar function—the potential-energy function is often used (Li, 2001; Dai and Liu, 2004). Potential-energy function is a function of distance or location, which can be superimposed. It is believed that each data object to any point in the field has the potential contributions, and the extent of the contributions is inversely proportioned with the square of the distance. Therefore, the data-int

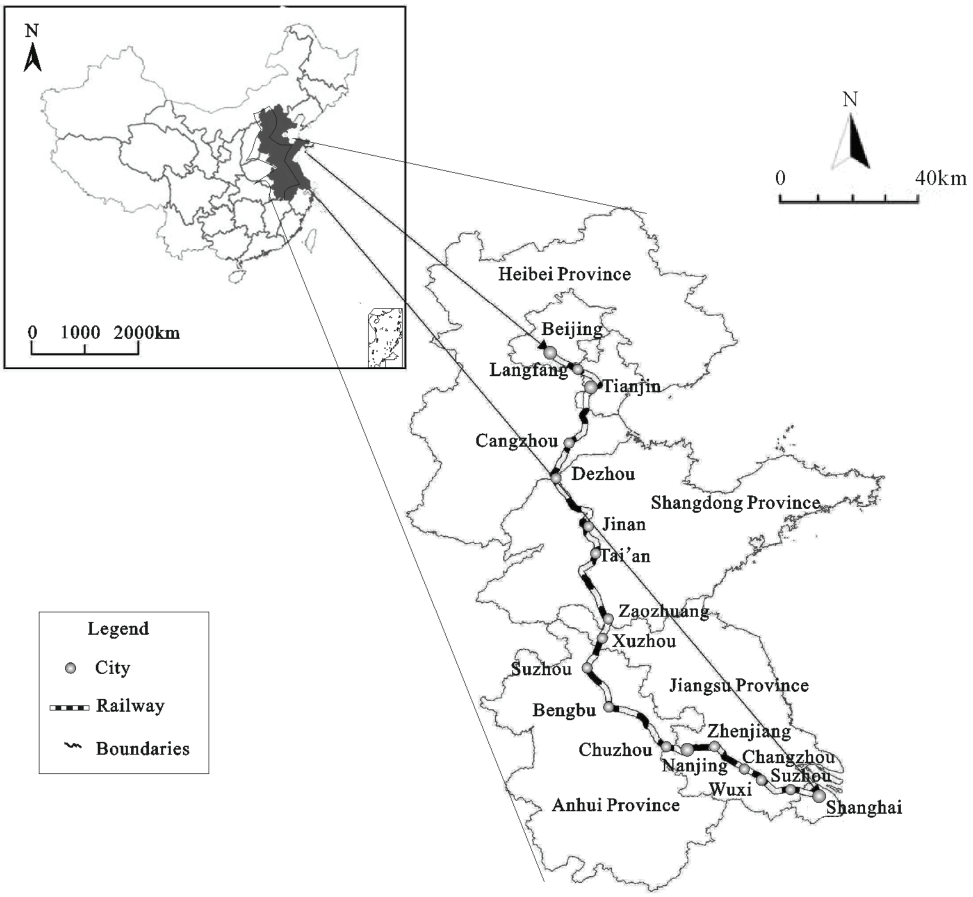


Fig. 1 Sketch map of study area

tensive areas should have greater potential-energy, while the data sparse areas have relatively small one.

3.2 City centricity index (CCI)

In order to facilitate the quantitative analysis, we choose a comprehensive index—"city centricity index (CCI)", based on the implication of the city centricity (Christaller, 1933). Generally, the higher the CCI is, the higher the economic and traffic development level is, and the bigger the city′s radiation potential energy is. The approach to computing the CCI can be summarized as follows:

First of all, we set an index system which reflects the urban economic capacity, including the financial revenue, gross domestic product (GDP), the proportion of the tertiary industry, the total industrial output, fixed asset investment volume and the foreign investment volume; besides, two important indexes are selected (the annual passenger volume and freight volume) in order to reflect the city's rail transport capacity; and we choose the urban non-agricultural population as an effective measure indicator to reflect the urbanization level of each city (Table 1).

Table 1 Index system of city centricity index

	Primary index	Secondary index
CCI	Urbanization level	Urban non-agricultural population (10^4 persons)
	Urban economic capacity	GDP ($\times10^6$ yuan (RMB))
		Financial revenue ($\times10^6$ yuan)
		Fixed asset investment ($\times10^6$ yuan)
		Foreign investment ($\times10^6$ yuan)
		Proportion of tertiary industry (%)
		Total industrial output ($\times10^6$ yuan)
	Urban rail transport capacity	Annual passenger volume ($\times10^4$ persons)
		Annual freight volume ($\times10^4$t)

Secondly, the data standardized processing is made before calculating the CCI to reduce the data's magnitude order differences.

Thirdly, as different indexes have different contributions to the urban development, this article used the Delphi method to weigh the different index's contribution. Based on this, each city's CCI can be calculated based on Equation (1).

$$CCI = \sum_{i=1}^{n} w_i \times u_i \quad (1)$$

where w_i is the weight of index i, and $\sum_{i=1}^{n} w_i = 1$; n is the number of the indexes; u_i is the standardized value of index i.

3.3 Improved data field model

The potential-energy function is based on inverse power-law or on negative exponential law, or even others (Kwan, 1998; Wilson, 2000), but the data field model is alterable when it is used to analyze the urban spatial interaction. The parameter values, especially the radiation factor and the radiation radius, are often determined by empirical analysis or by physical analogy. As early as in the period of ''quantitative revolution" of geography, geographers tried in vain to derive the parameter values as constants of the model from theoretical distribution of probability.

In the regional space, it is proved that the urban spatial interaction systems are either fractal networks or evolving into self-similar systems (Arlinghaus, 1985; Wong and Fotheringham, 1990; Batty and Longley, 1994; Chen and Zhou, 2001), and the city is often not distributed isolatedly, which means, each city in the region shows its radiation influence on other cities in the region, thus forming the urban data field.

In the urban data field, the potential-energy function of point x is defined as the whole influence of all the nodes (cities). We choose n nodes (according to the cities' geographical locations from north to south) in a region, and the potential-energy function of point x in the space can be expressed in Equation (2):

$$F(x) = \sum_{i=1}^{n} CCI_i \mathrm{e}^{\frac{-\{d(x,\, i)\}^2}{2\delta_i^2}} \quad (2)$$

where F is the radiation potential-energy, which denotes the urban interaction, $d(x, i)$ is the distance from the point x to node i, CCI_i is the city centricity index of node i and δ_i is radiation factor of node i. δ_i comes from the classical physics analogy and there is no reason whatsoever for this to hold for economic- and social-geographical systems. In this study, the spatial radiation field has a close relationship with the CCI, δ_i can be defined as $\delta_i = CCI_i \times CCI_i$. Furthermore, as the data sets are large, in order to reduce the complexity of computing, this article chose the "3δ rule" in the Gaussian distribution law to determine the city spatial radiation radius (R), that is, $R \approx 3 \times \delta_i$.

3.4 Computational procedure

Generally speaking, the approach to model the spatio-temporal interaction of cities can be summarized in three steps:

Step 1: In order to derive the data field model from general equation, two basic assumptions should be given as follows: first, the basic unit was set as 1×1km grid in the study areas; secondly, every CCI value has an equivalent spatial radiation field in every grid.

Step 2: Calculation of the radiation factor (δ_i) of each city, and then computation of the radiation potential-energy (F).

Step 3: Computation of the spatial radiation radius (R), and according to this, the urban spatial interaction can be measured from the spatial aspect.

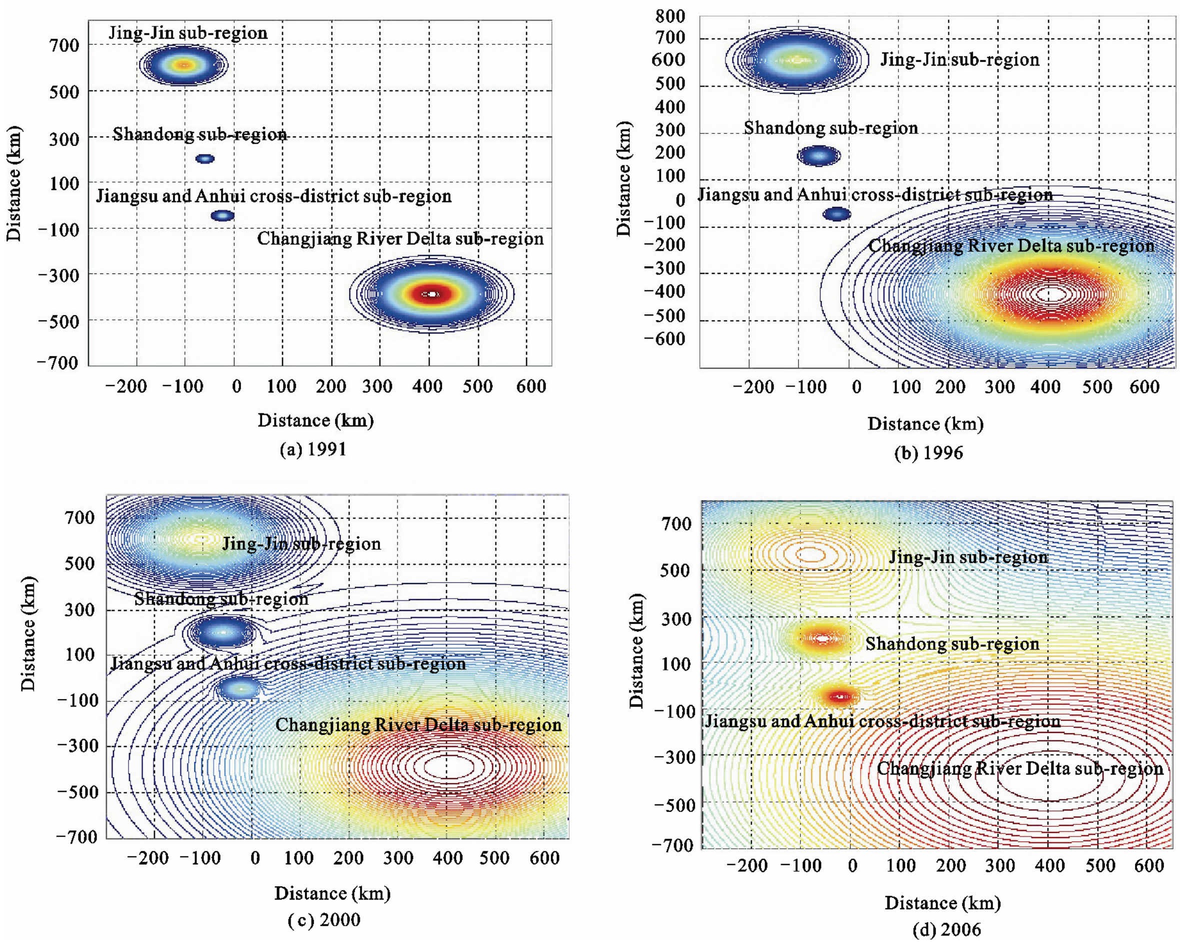
The above computation procedure can be implemented by using mathematical software Matlab7.0.

4 Results and Analysis

4.1 General urban spatial interaction of Beijing-Shanghai Corridor

The Beijing-Shanghai Corridor can be divided into four sub-regions according to their different features of economic development, that is the Jing-Jin (Beijing-Tianjin) sub-region (including the cities of Beijing, Tianjin, Langfang, Cangzhou), the Shandong sub-region (including the cities of Dezhou, Jinan, Tai'an, Zaozhuang), the sub-region of Jiangsu and Anhui cross-district (including the cities of Xuzhou, Suzhou, Bengbu, Chuzhou), and the Changjiang River Delta sub-region (including the cities of Nanjing, Zhenjiang, Wuxi, Changzhou, Suzhou, Shanghai). Then the overlay analysis of the spatial radiation field of all the cities in each sub-region can be easily conducted based on the assumption that the city with the highest CCI is the center of gravity as well as the spatial radiation field center in this sub-region (Fig. 2).

According to the analysis by above methods, it is observed that:



In Fig. 2, Fig. 3, and Fig. 4, Zaozhuang City is the zero point in the coordinate system

Fig. 2 Change of spatial radiation field of sub-regions from 1991 to 2006

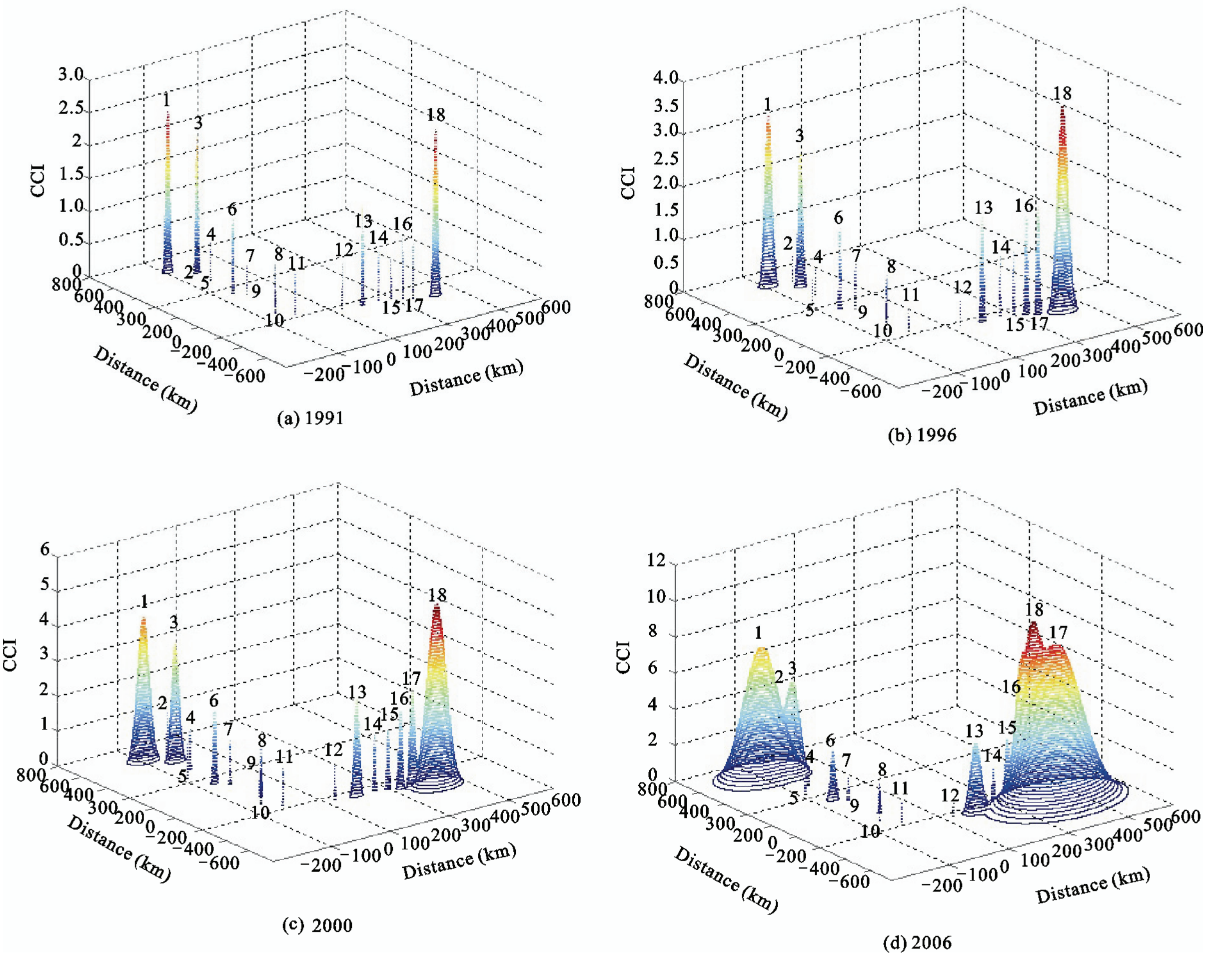
(1) The evolution of the spatial radiation field of the sub-regions from 1991 to 2006 is mapped in Fig. 2. As expected, the intensity of the spatial interaction of each sub-region was increasing. In general, the spatial interactions of the sub-regions in the Beijing-Shanghai Corridor showed a spatio-temporal evolution model of “spatial aggregation—axial expansion—networking interaction”.

(2) In the period of 1991–1996, the spatial interaction among different sub-regions was very weak (Fig. 2a, 2b). However, as the radiation potential-energy of the cities in each sub-region grew, the internal spatial interaction among sub-regions was strengthening. It can be seen clearly from the evolution track (from 2000 to 2006) that the sub-regions’ spatial interaction were expanding along the traffic line with the increase in the cities’ radiation potential-energy and eventually formed a complex network-connecting spatial structure (Fig. 2c, 2d).

(3) Another interesting finding is that spatial division among different sub-regions was obvious, although the spatial radiation field of each sub-region tended to expand. On the one hand, the spatial radiation field of the developed sub-regions like the Changjiang River Delta sub-region and the Jing-Jin sub-region has a notable rate of expansion, and their spatial radiation fields have already been spatially overlapping. On the other hand, the spatial radiation field of the less-developed sub-regions such as the sub-region of Jiangsu and Anhui cross-district and the Shandong sub-region was gradually covered by Changjiang River Delta sub-region and the Jing-Jin sub-region.

4.2 Urban spatial interaction in key sub-regions

The urban spatial radiation field of 18 cities were decreasing gradually from internal to external, showing a "multi-peaks and one deep valley" spatial pattern in the Beijing-Shanghai Corridor, where the main peaks are formed by the cities with the high radiation potential-energy and the high CCI value (Fig. 3).



1. Beijing 2. Langfang 3. Tianjin 4. Cangzhou 5. Dezhou 6. Jinan 7. Tai′an 8. Zaozhuang 9. Xuzhou 10. Suzhou
11. Bengbu 12. Chuzhou 13. Nanjing 14. Zhenjiang 15. Changzhou 16. Wuxi 17. Suzhou 18. Shanghai

Fig. 3 Change of urban spatial radiation potential-energy from 1991 to 2006

4.2.1 Changjiang River Delta and Jing-Jin sub-region

As the two developed metropolitan areas in China, spatial interaction within the Changjiang River Delta and the Jing-Jin sub-regions displayed the following characteristics:

(1) The two sub-regions had strong spatial radiation capability and high radiation potential-energy.

(2) The urban spatial radiation field of cities in the two sub-regions had overlapped, which greatly enhanced their whole radiation potential-energy and showed the notable “field effect” in space.

(3) The scope and intensity of the spatial radiation field of the Jing-Jin sub-region were weaker than those of the Changjiang River Delta sub-region. This indicates that the urban spatial interaction within the Jing-Jin sub-region was relatively weak, which might be due to the lack of mechanism of effective cooperation and communication among cities in this sub-region.

4.2.2 Sub-regions in central part of Beijing-Shanghai Corridor

There are many small and poor cities in the central part of the Beijing-Shanghai corridor. Those cities belong to the sub-region of Jiangsu and Anhui cross-district and the Shandong sub-region. Evolution of spatial interactions among those cities had the following spatial features:

(1) All the cities in these two sub-regions had weak radiation potential-energy and small spatial radiation field, the intensity of urban spatial interaction was also very weak. In particular, there existed a low radiation potential-energy zone between Nanjing and Bengbu, i.e. Chuzhou City has weak radiation potential-energy. Besides, the radiation potential-energy and spatial radiation field of the Shandong sub-region were also very limited.

(2) The urban spatial interaction within the sub-region of Jiangsu and Anhui cross-district differs in certain

degree from that of the Shandong sub-region. It is observed that Shandong sub-region tended to link the Jing-Jin sub-region spatial radiation field, while the of Jiangsu and Anhui cross-district was more inclined to be integrated into the spatial radiation field of Changjiang River Delta sub-region. This result has reflected the fact that the urban spatial interaction is highly influenced by distance: the Shandong sub-region, which is closer to Jing-Jin sub-region, has greater spatial interaction intensity with Jing-Jin sub-region. However, sub-region of Jiangsu and Anhui cross-district has a closer economic and traffic relationship with Changjiang River Delta sub-region because of a shorter distance between the two sub-regions. Therefore, its spatial interaction intensity with the Changjiang River Delta sub-region is much stronger.

4.3 Spatial interaction of cities

Furthermore, from the analysis through the data field model, it is also observed that:

(1) Based on the macro-level analysis of the corridor, it is recognized that cities within each sub-region are interrelated mutually. Moreover, polarization and diffusion effects of all the sub-regions enhance continuously with economic growth, and these effects finally formed a spatial interaction system with organic connection in the Beijing-Shanghai Corridor. As a result, urban spatial interaction has become the basic force of the urban spatial distribution within the corridor.

(2) From a meso-scale perspective to analyze the inter-city spatial interaction, the improvement of transport capacity and economic development from 1991 to 2006 created favorable conditions for the enhancement of radiation potential-energy, the expansion of spatial radiation field and the formation of network-connecting spatial patterns within the Beijing-Shanghai Corridor. Those in turn facilitate the developments of production and labor markets, etc., and thus lead to the notable improvement of inter-city spatial interaction efficiency in the corridor.

(3) Through a micro-level analysis of these cities, it can be found that the CCI continuously increases, and urbanization rate and the CCI present high level of correlation (R^2 were 0.91, 0.88, 0.86, 0.82 in 1991, 1996, 2000, 2006, respectively), which indicated that the urban development is accompanied with the expansion of spatial radiation field (Fig. 4). As a result, the spatio-temporal distances among the cities are shortened and their location advantage is improved. Particularly, the radiation radius of the Changjiang River Delta sub-region was expanding faster than that of the Jing-Jin (Beijing-Tianjin) sub-region, and their radiation radiuses extended faster than other sub-regions. It can be concluded that some big cities with high level of globalization (such as Beijing, Shanghai, Tianjin, Nanjing) benefit much more than the local cities, although the spatial radiation field of all the cities within the corridors present an extending trend (Fig. 3). In addition, with the accelerating process of regional economic integration, these big cities and the developed urban agglomeration areas will have a more obvious impact on the further selection of the location of economic activities.

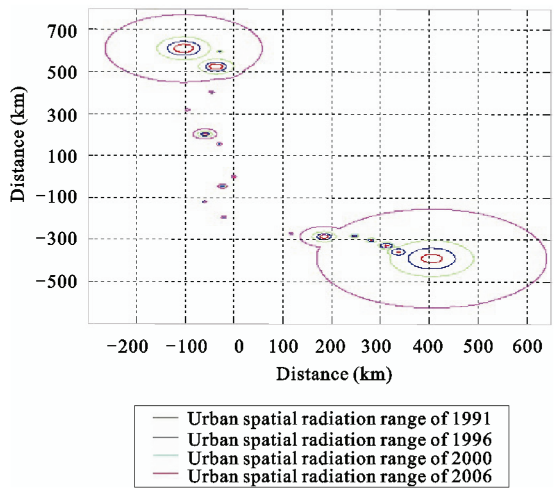


Fig. 4 Change of urban spatial radiation field's range from 1991 to 2006

5 Conclusions and Discussion

This study examines the spatial and temporal pattern of urban spatial interaction change as a result of urban economic growth and traffic development by taking the Beijing-Shanghai Corridor as a case. The Beijing-Shanghai Corridor is characterized by a substantial increase in urban radiation potential-energy and the expansion of urban spatial radiation field. Geographically, the inter-city spatial interaction can re-organize these cities in Beijing-Shanghai Corridor as a joint system. Cities with location advantage have gained more benefits from that. Besides, the extension of the spatial radiation fields of these cities reveal the expansion of their market-service-scope and the expansion of their resources hinterlands, which will help to promote regional economic aggregation and make the core of urban areas' spatial expansion from zero-dimensional model to the multi-dimensional pattern.

Nevertheless, the case of Beijing-Shanghai Corridor can not be taken to draw the overall picture of the entire country. What has distinguished Beijing-Shanghai Corridor is its characteristic as the most globalized corridor in China, which has greatly facilitated the expansion of urban radiation field more significant than that in other Chinese cities and regions. Further studies are needed to analyze the inter-relationship between the change of urban spatial interaction and urban development in other Chinese cities with different administrative, demographic, and geographic characteristics.

The urban data field model developed in this paper and the computational results given above help us apprehend the dominative rules in both physical systems and human systems. The similarities and differences between the data field model used in geography analysis and in other disciplines are obvious. However，this is not the case. Similarity indicates that geographical systems follow physical laws to some extent, while differences imply that the rules of geographical evolution differ from those in physical systems. In fact, an adoption of other factors (such as the environmental protection, etc.) into the existing index systems that describe the urban spatial interactions may help overcome the current defects and shed new lights on the interactions between the change of urban spatial interaction and its underlying driving forces.

Moreover, the comparison between the data field model in geography and the law of radiation in physics will help deeply understand and probe into the essence of nature. It is just the harmony between symmetry of physical laws and geographical laws that ensure the order of the world. It is hoped that our application of the new physics model to urban research as demonstrated in this study can open up a new era of comparative research so as to shed light on the pattern and process of urban spatial interaction in China and even the world.

Acknowledgements

The authors would like to thank Mr. Tian Shanchuan, Miss. Chen Li at Institute of Geographic Sciences and Natural Resources Research for insightful comments and authors are especially grateful for the anonymous reviewers for their comments and suggestions on the earlier draft of this manuscript.

References

Aljarad S N, Black W R, 1995. Modeling Saudi Arabia-Bahrain corridor mode choice. *Journal of Transport Geography*, 3: 257–268. DOI: 10.1016/0966-6923(95)00025-9

Alonso W, 1978. A theory of movements. In: Hansen N M (eds.). *Human Settlement Systems: International Perspectives on Structure, Change and Public Policy.* Cambridge, Massachusetts: Ballinger Publishing Company, 197–211.

Arlinghaus S, 1985. Fractals take a central place. *Geogr. Ann.*, 67B: 83–88.

Batty M, Longley P A, 1994. *Fractal Cities: A Geometry of Form and Function.* London: Academic Press, 26–39.

Chen Yanguang, Zhou Yixing, 2001. A study of multifractals measures of the spatial structure of the urban system in Central Plains. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 37(6): 810–818. (in Chinese)

Chen Yanguang, Zhou Yixing, 2004. Multi-fractal measures of city-size distributions based on the three-parameter Zipf model. *Chaos, Solitons & Fractals*, 22: 793–805. DOI: 10.1016/j.chaos.2004.02.059

Christaller W, 1933. *Central Places in Southern Germany.* Englewood Cliffs: Prentice Hall, 28–56.

Dai Xiaojun, Liu Changyu, Han Xu et al., 2004. Application of data field in information token. *Journal of Fudan University* (*Natural Science*), 43(5): 933–938. (in Chinese)

Fotheringham A S, 1983. A new set of spatial interaction models: The theory of competing destinations. *Environment and Planning A*, 15(1): 15–36.

Gaubatz P, 1999. China's urban transformation: Patterns and processes of morphological change in Beijing, Shanghai and Guangzhou. *Urban Studies*, 36(9): 1495–1521. DOI: 10.1080/0042098992890

James P E, Martin G J, 1981. *All Possible Worlds: A History of Geographical Ideas.* (2nd ed.). New York: John Wiley & Sons, 25–34.

Kirkby R J R, 1985. *Urbanization in China: Town and Country in A Developing Economy, 1949–2000AD.* New York: Columbia University Press, 207.

Kwan M P, 1998. Space-time and integral measures of individual accessibility: A comparative analysis using a point-based framework. *Geographical Analysis*, 30(3): 191–216.

Li Deren, 2001. On spatial data mining and knowledge discovery. *Geomatics and Information Science of Wuhan University*, 26(6): 491–499. (in Chinese)

Ma L J C, 2002. Urban Transformation in China, 1949–2000: A review and research agenda. *Environment and Planning A*, 33(9): 1545–1569. DOI: 10.1068/a34192

Makse H A, Andrade Jr J S, Batty M et al., 1998. Modeling urban growth patterns with correlated percolation. *Phys. Rev. E.*, 58(6): 7054–7062. DOI: 10.1103/PhysRevE.58.7054

Makse H A, Havlin S, Stanley H E, 1995. Modeling urban growth patterns. *Nature*, 377: 608–612. DOI: 10.1038/377608a0

Manrubia S, Zanette D, 1998. Intermittency model for urban development. *Phys. Rev. E.*, 58(1): 295–302. DOI: 10.1103/PhysRevE.58.295

National Bureau of Statistics of China, 1992, 1997, 2001, 2007. urban Statistical Yearbook of China, 1991, 1996, 2000, 2006. Beijing: China Statistics Press. (in Chinese)

National Bureau of Statistics of China, 2005. Statistical Yearbook of China. Beijing: China Statistics Press. (in Chinese)

Pannell C W, 1990. China's urban geography. *Progress in Human Geography*, 14(2): 214–236.

Pannell C W, 2002. China's continuing urban transition. *Environment and Planning A*, 34(9): 1571–1589. DOI: 10.1068/a34201

Wang Zheng, Ding Jinhong, 1994. *Regional Scientific Principle.* Beijing: Science Press, 38–55. (in Chinese)

Whebell C F J, 1969. Corridors: A theory of urban systems. *Annals of the Association of American Geographers*, 1: 1–26.

Wilson A G, 1967. A statistical theory of spatial distribution models. *Transportation Research*, 1: 253–269.

Wilson A G, 1970. *Entropy in Urban and Regional Modeling.* London: Pion Press, 56–70.

Wilson A G, 1971. A family of spatial interaction models and associated developments. *Environment and Planning*, 3(1): 1–32.

Wilson A G, 2000. *Complex Spatial Systems: The Modeling Foundations of Urban And Regional Analysis.* Singapore: Pearson Education South Asia Pte Ltd, 79–86.

Wong D, Fotheringham A S, 1990. Urban systems as examples of bounded chaos: Exploring the relationship between fractal dimension, rank-size, and rural to urban migration. *Geogr. Ann.*, 72B: 89–99.

Xue Ling, Yang Kaizhong, 2005. Spatial planning of commercial allocation in Haidian District in Beijing based on spatial interactive model. *Geographical Research,* 24(2): 265–268. (in Chinese)

Zanette D, Manrubia S, 1997. Role of intermittency in urban development: A model of large-scale city formation. *Phys. Rev. Lett.*, 79(3): 523–526. DOI: 10.1103/PhysRevLett.79.523