

# Understanding spatial structures and organizational patterns of city networks in China: A highway passenger flow perspective

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**Abstract:** The use of multi-perspective and multi-scalar city networks has gradually developed into a range of critical approaches to understand spatial interactions and linkages. In particular, road linkages represent key characteristics of spatial dependence and distance decay, and are of great significance in depicting spatial relationships at the regional scale. Therefore, based on highway passenger flow data between prefecture-level administrative units, this paper attempted to identify the functional structures and regional impacts of city networks in China, and to further explore the spatial organization patterns of the existing functional regions, aiming to deepen our understanding of city network structures and to provide new cognitive perspectives for ongoing research. The research results lead to four key conclusions. First, city networks that are based on highway flows exhibit strong spatial dependence and hierarchical characteristics, to a large extent spatially coupled with the distributions of major megaregions in China. These phenomena are a reflection of spatial relationships at regional scales as well as core-periphery structure. Second, 19 communities that belong to an important type of spatial configuration are identified through community detection algorithm, and we suggest they are correspondingly urban economic regions within urban China. Their spatial metaphors include the administrative region economy, spatial spillover effects of megaregions, and core-periphery structure. Third, each community possesses a specific city network system and exhibits strong spatial dependence and various spatial organization patterns. Regional patterns have emerged as the result of multi-level, dynamic, and networked characteristics. Fourth, adopting a morphology-based perspective, the regional city network systems can be basically divided into monocentric, dual-nuclei, polycentric, and low-level equilibration spatial structures, while most are developing monocentrically.

**Keywords:** space of flows; city network; urban economic region; urban system; monocentric structure; polycentric structure; community detection

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## 1 Introduction

Towards the end of the second millennium of the Christian era, in concert with the deepening processes of globalization and digitalization, massive developments in information technology, telecommunications, and modern transportation led to dramatic regional economic revolutions (Taylor *et al.*, 2002; Castells, 2010). Data show that both growth in production and spatial organization follow a diversified trend, while a transformation took place that led to contemporary regional economies being gradually dominated by functional networked space rather than hierarchal space based on administrative units (Liu and Zhen, 2004). Thus, alongside the “space of flows”, cities have become increasingly involved in the diversified flows of global production factors. The study of city networks, as examples of flow systems, has emerged as a consequence of this background. As a new type of spatial organization that originated in the age of globalization and information, city network refers to horizontal and non-hierarchical relational geographies between similar or complementary cities and emphasizes specialized division of labor and externality (Camagni and Capello, 2004). In current research, hierarchical structures have long provided the traditional perspective underlying understanding of urban systems. However, in the contemporary context of urban geography, more attention has been placed on the structure, function, and relationships of city networks within multi-scalar spaces (Taylor *et al.*, 2010).

Inspired by the “space of flows” theory (Castells, 1996), a new research agenda has developed within urban studies that emphasizes relational geography. In this context, research on multi-level and multi-scalar city networks has substantially enriched our understanding of both spatial logic and regional cognition. These approaches have even led to breakthroughs and innovations in methods and theory. Thus, at present, research on city network can be broadly divided into two main schools including “world city network” (Taylor *et al.*, 2001) and “polycentric urban region” (Hall and Pain, 2006) that are focused respectively at either global (or national) or regional scales (Malecki, 2002; Hoyler *et al.*, 2008; Taylor *et al.*, 2009). In empirical studies, measurements of city networks at different spatial scales have mainly been conducted using infrastructural networks (Alderson and Beckfield, 2004; Derudder and Witlox, 2008), enterprise organizations (Beaverstock and Smith, 1996; Taylor *et al.*, 2009), or social culture relationships (Taylor, 2004).

Compared to other approaches, the use of infrastructural networks appears most efficient. This approach can be subdivided into two categories, the first of which deals with transport infrastructure, including the intercity passenger and cargo flows of air, railway and so on, as representative of the linkages between cities. The second category is communication infrastructure, specifically the use of the Internet, telephone communications, and postal service flows to describe city network structures. Research on Chinese city networks has flourished in recent years, characterized by emphasis on transport infrastructure (Yu *et al.*, 2008; Zhong and Lu, 2011), the organization of enterprise (Derudder *et al.*, 2010; Zhao *et al.*, 2015), and Internet communication (Dong *et al.*, 2014; Zhen *et al.*, 2016). As a consequence, the research methods in this field tend to employ social and complex networks to calculate topological properties, which contribute to the extraction of city network structural features. Previous studies, however, have more or less ignored the influence of geographical space and have not incorporated a comprehensive understanding of the internal logic of city networks.

City networks can be mapped using intercity relationships, which to some extent are af-

affected by city hierarchy, geographical distance, and their spatial interactions (Chen *et al.*, 2015). These factors mean that high-ranking cities have tended to overcome the constraints of geographical distance and achieve frequent intercity factor flows. Because the strength of these flows decays as geographical distance increases, it is worthwhile to investigate the interactions between city hierarchy and city network development, as well as the role played by geographical distance in this process. Interregional flows of passengers and goods are important indexes used to effectively reflect city networks as they are naturally sensitive to geographical distance. However, because of data acquisition limits, contemporary research on city network from the perspective of traffic infrastructure has mainly utilized flow data of airway and railway. Research on highway flows has mostly been conducted relatively recently and so limited attention has been given to city networks and regional interactions at macroscopic scales. Highways enable short distance transportation and so exhibit significant spatial dependence and distance decay characteristics. For these reasons, highway flows can adequately and clearly describe the functional interactions between cities within an entire regional system.

Thus, incorporating highway flow data between 289 prefecture-level administrative units, the community detection method and spatial visualization are applied in this study to investigate the roles played by city hierarchy and geographical distance in the network development of cities. The aim of this research is to describe the functional structure and regional effects of China's city networks from the perspective of highway flows. At the same time, spatial organizational patterns are also extracted and used to determine inherent rules. In addition to providing a new approach and cognitive perspective to the study of city networks, this research also enables a deeper understanding of the process of spatial reorganization in the ongoing localization and globalization context.

## 2 Data sources and methods

### 2.1 Data sources

Although statistical data derived from flights and railway movements have been widely applied in previous studies to analyze traffic flows, limited highway passenger flow data has been available at the national scale. Similarly, data that is available is often flawed due to sampling shortcomings and poor instantaneity. These issues can be overcome, to some extent, by utilizing data grabbing from Internet as this is more dynamic and has broader coverage. In this paper, we utilize raw data from intercity bus schedules that link 289 prefecture-level administrative units. We constituted these schedules into a  $289 \times 289$  symmetrical matrix that comprises a total of 83,232 relational values as proxies for the strength of spatial interactions between Chinese cities. To mitigate the potentially huge workload involved in data collection for this study, we mainly employed a web page retrieval strategy, accessing passenger service websites (e.g., checi.cn) and then extracting intercity linkage data using a cyclic query technique. All data were also randomly extracted manually and cross-examined to ensure their completeness and accuracy. To be more specific, except national holidays, the bus schedules of most cities in China are relatively fixed, so we consider schedule data for one day to be representative. The data extraction was carried out under C# language environment, and the operation date was April 15th, 2014.

## 2.2 Methods

### 2.2.1 Community detection

In the study of network science, a community refers to a network subset. The nodes of the network can be grouped into sets of nodes so that each community is closely connected internally with sparser connections between groups. The identification of densely connected groups, based on topological relationships and network attributes, is referred to as community detection. Community detection, which is crucial for understanding network structures in the real world, has long been one of the outstanding issues in complex network, and the mainstream algorithms at present include Girvan-Newman (Girvan and Newman, 2002), Walktrap (Pons and Latapy, 2006), Fast-greedy (Clauset *et al.*, 2004), Multi-level (Blondel *et al.*, 2008), Label Propagation (Raghavan *et al.*, 2007), and Infomap (Rosvall and Bergstrom, 2008) algorithms.

Among these algorithms, Rosvall and Bergstrom (2008) proposed the well-known Infomap algorithm based on flow and information theory. The main idea is to measure connectivity between nodes through information flow within the entire network, making information flow inside community significant larger than that between communities (Figure 1). Specifically, the Infomap algorithm identifies communities within directed and weighted networks via the combined use of random walks and compression principles. First of all, each node within a network can be denoted by a unique codeword based on the visiting frequency of the random walk. Further, shorter codewords are assigned to more frequently visited nodes using Huffman coding. Then, the random walk trajectory of a network can be described by applying two levels, prefixed community codewords and the suffixed codewords of nodes inside the communities. Therefore, the clustering problem can be expressed as finding the partition that yields the minimum description code length. Essentially, this algorithm incorporates code length of the random walk as an objective function and thus transforms the issue of network partition into the problem of code compression of minimum description length.

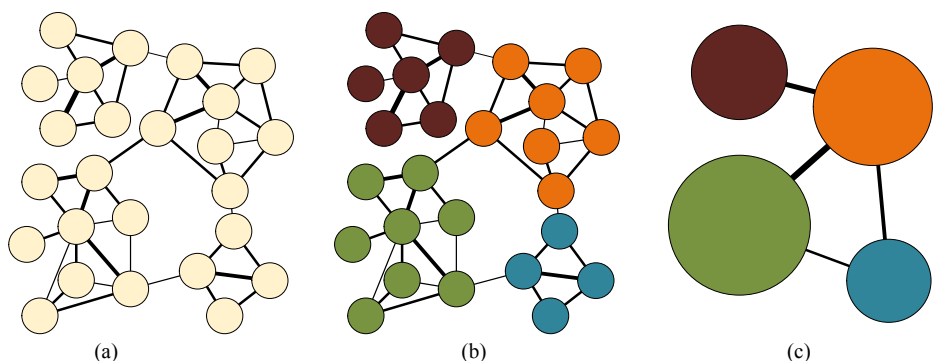
According to Shannon's source coding theorem, if we use  $n$  codewords to describe the  $n$  states of a random variable  $X$  that occur with frequencies  $p_i$ , the average length of a codeword can be no less than the entropy of the random variable  $X$  itself:

$$H(X) = -\sum_{i=1}^n p_i \log(p_i) \quad (1)$$

This expression provides a lower bound on the average length of codewords in each codebook. To calculate the average length of the code describing a step of the random walk, we need only to weight the average length of codewords from the index codebook and the module codebooks based on their rates of use. This is the map equation:

$$L(M) = qH(Q) + \sum_{i=1}^m p_i H(P_i) \quad (2)$$

In this expression,  $L(M)$  denotes the expectation of average code length that the random walk spends inside and outside communities;  $q$  is the probability to exit module  $i$ ;  $H(Q)$  is the frequency-weighted average length of codewords in the index codebook;  $p_i$  is the probability to visit any node that the random walk spends in module  $i$ ;  $H(P_i)$  is the frequency-weighted average length of codewords in module codebook  $i$ .



**Figure 1** Detecting communities of information flows within networks

In terms of network data, node weight, edge weight, and linkage direction are important attributes for illustrating community structures in the real world network. However, most of the traditional algorithms are currently unable to take directed and weighted networks into consideration and so often implement network partitioning that does not incorporate actual attribute information of linkage weight and direction. Thus, different algorithms exhibit variable performance characteristics depending on environment and may even be significantly biased compared to reality. The Infomap algorithm, which is almost the only algorithm that can consider topological properties such as node weight, edge weight and linkage direction and also can take higher-order network data into consideration, exhibits significant adaptability and consistent performance. The related research has shown that the Infomap method has been one of the best performing community detection algorithms (Lancichinetti and Fortunato, 2009; Zhong *et al.*, 2014) suitable for weighted and directed networks. Here, we see a city as a node of networks and the linkage strength of a city as the weight of a node. Thus, the network edges can be expressed via the intercity linkages and the edge weights can be expressed via the linkage frequencies between cities. All data processing and algorithm implementation were performed on the R platform (Csardi and Nepusz, 2006).

### 2.2.2 Network visualization

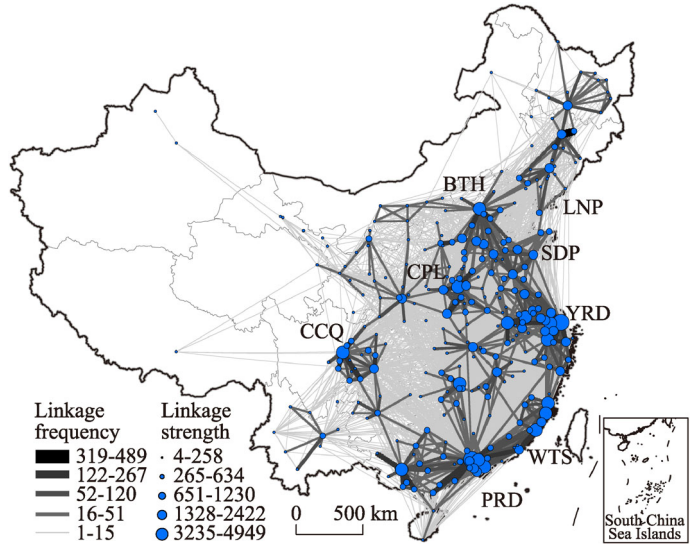
Geographical science emphasizes spatial patterns, processes, and internal logic of “space of flows”; thus, statistical modeling and visualization provide key approaches to quantitatively measure “space of flows”. Generally speaking, topological networks can have a good performance in describing topological relationships and attributes, especially accurately depicting the detailed characteristics of networks. However, they often tend to lose effectiveness when indicating geographical space. Geographical networks have natural advantages in expressing spatial structures and forms of real geographical environments, while their drawbacks in portraying detailed features emerge when facing large data volume in complex network analysis. Therefore, we attempt to integrate topological and geographical networks in this study in order to enable a deeper understanding of the spatial structures and organizational patterns of city networks in China based on highway flows.

Chord Diagram, as a new-type topological network visualization method, enables us to convert network data into graphical representation that has been widely adopted to interpret topological relationships and attributes of nodes in networks. Specifically, chord diagram takes each node as an arc and the linkage between arcs as a chord; the arcs with different

colors indicate different nodes while the chords with different colors express different topological relationships between different nodes, and the relative sizes of arcs and chords depend on the attributes of nodes and linkages between nodes.

### 3 The macro-spatial configuration of China's city networks

In traditional studies, the connections between cities and regions, which can be measured through geographical factor distribution or the use of gravity models, have been used to illustrate hierarchical structures and static patterns. Nevertheless, contemporary urban studies based on relational data have led to new perspectives that are more open, dynamic, and networked; the highway flow values are typical examples of such new relational data. As demonstrated in Figure 2, the macro-



**Figure 2** The macro-spatial configuration of China's city networks

spatial configuration of city networks in China was visualized. The spatial distribution of highway flows shows significant spatial heterogeneity and the spatial correlation form of city networks represents strong spatial dependence and hierarchical characteristics. Furthermore, these macro-spatial patterns also reveal obvious spatial coupling with major megaregions in China and predominantly reflect the spatial relationships and core-periphery structures at regional scales.

On the whole, the intercity highway flows are mainly distributed in eastern coastal areas, especially within the megaregions of Beijing-Tianjin-Hebei (BTH), Shandong Peninsula (SDP), Yangtze River Delta (YRD), Western Taiwan Straits (WTS), and Pearl River Delta (PRD), together constituting a dense and spatially-correlated urban belt in China. In addition to these regions, the major economic zones of northeastern, central, and western China, based on the core cities, form the city regions of intense external flows. In terms of intercity spatial correlation, the YRD megaregion comprises a polycentric, multi-level city network pattern. The urban areas within this region tend to be closely interconnected, while the economic impact of the YRD megaregion has spread into neighboring Anhui Province. Similarly, the PRD megaregion, including the core cities of Guangzhou and Shenzhen, is characterized by a morphology that consists of highly external linkages and a certain degree of connectivity to neighboring provincial units of Fujian and Guangxi. The BTH megaregion, in contrast, centered on the megacity of Beijing, is characterized by the formation of radial associations with surrounding regions. Some of these connections extend southwards to cities in western Shandong Province, establishing the Beijing-Tianjin-Hebei-Shandong city

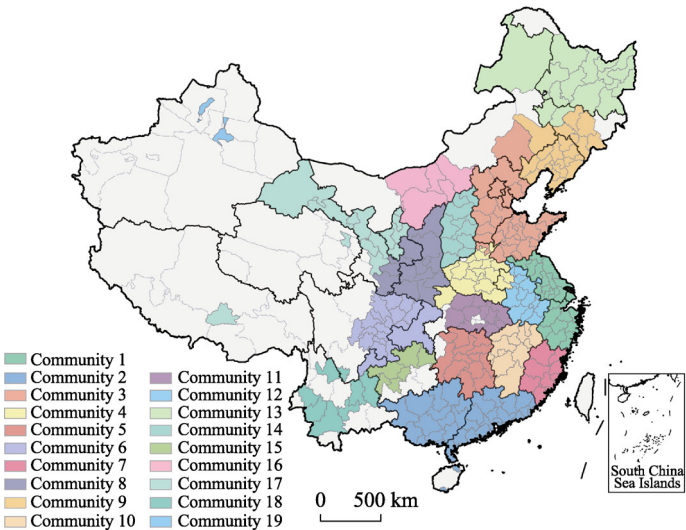
networks. The Chengdu-Chongqing (CCQ) region is also characterized by the presence of intertwined city networks with surrounding cities, showing typical dual-nuclei driving development dynamics. In contrast, although the Central Plains Economic Zone (CPL) is characterized by a relatively high average network density, it nevertheless still conforms overall to a monocentric trend in development. In northeastern China, it has constituted a radial spatial correlation pattern based on the central city of Harbin in the northern part, and the central Jilin megaregion is characterized by the highest connectivity between the cities of Changchun and Jilin, and the Liaoning Peninsula (LNP) megaregion is concentrated on the nodal city of Shenyang in the south. Although interactive networks within provincial units are also seen in other regions of China, their overall connectivity remains relatively weak compared to the above major megaregions.

#### 4 Regional effects of city networks in China

Based on highway flows between cities, we subdivided 289 prefecture-level administrative units into 19 communities using the community structure detection method (Infomap algorithm), in which nodes are more closely interconnected than nodes outside the communities, as shown in Figure 3. In terms of the spatial scale, these communities are smaller than the traditional regional division of “the Three Regions”<sup>1</sup> and “Four Major Economic Regions”<sup>2</sup>, they are nevertheless larger than either metropolitan areas or megaregions. In this study, we suggest they are correspondingly urban economic regions for identifying the regional structures of intercity relationships within China. Urban economic region, as an emerging spatial organization mode in the functional regional system of China, has engendered a fresh perspective and understanding in terms of framing urban and regional space. In comparison with the previous division schemes (Gu, 1991; Zhou and Zhang, 2003), our empirical findings show some similarity, but some new urban and regional structures have been identified. Specifically, the spatial implications are demonstrated as follows:

##### (1) Administrative region economy

Administrative boundary is a fundamental element to understand regional economy and spatial interaction. The urban economic regions identified on the basis of spatial linkages, are certainly consis-



**Figure 3** Community structures based on spatial linkages

<sup>1</sup> Traditionally, China has long been divided into eastern, central, and western regions on the basis of the natural background and the socioeconomic development status in the national macro policy system for a long time.

<sup>2</sup> In recent years, in order to scientifically reflect the socioeconomic development status, Chinese government agencies have divided the national economic region into the eastern, the central, the western, and the northeastern China.

tent with the provincial administrative boundaries to a great extent, showing significant characteristics of administrative economy. On the one hand, some provincial administrative boundaries are basically resulted from the natural geographical borders. For example, the Taihang Mountains are the borders between Shanxi and Hebei provinces; the Wuyi Mountains running along the boundary between Jiangxi and Fujian provinces; and the Nanling Mountains are the natural boundaries separating Guangdong Province and Guangxi Zhuang Autonomous Region from Fujian, Jiangxi and Hunan provinces. Due to these physical geographical barriers, some regions form relatively closed or semi-closed regional economic spaces, such as the provinces of Fujian, Jiangxi, Hunan and Sichuan. In these regions, there are internally higher connections between cities, while lower intensities with cities outside these areas. On the other hand, under the institutional framework of “dominant government, weak market” and “top-down decentralization” in contemporary China, cities tend to exhibit significant advantages in terms of resource allocation, factor mobility, infrastructure sharing, and regional division and coordination within the same province and thus develop into individual regional economic system within the inherent territories. Indeed, due to these factors such as administrative governance system and policy barrier, factor mobility across administrative borders can usually be constrained and hindered to a considerable degree.

### (2) Spatial spillover effects of megaregions

Megaregions, as globalization's new urban form, constitute trans-metropolitan landscapes comprising networked urban centers and their surrounding areas (Harrison and Hoyler, 2015). Within megaregions, the presence of enhanced socioeconomic activities has exerted correspondingly strong influence on the formation of dense inter-regional or even inter-provincial linkages that span administrative borders and has thus led to marked spatial spillover effects. As is mapped in Figure 3, there are some urban economic regions crossing provincial administrative boundaries including Community 1, Community 2 and Community 3. In eastern China, Shanghai, Jiangsu and Zhejiang provinces are divided into one community (Community 1). The YRD megaregion centered on Shanghai, as the most developed region in China, has strong economic radiation capacities and frequent factor flows. Regional spatial structures tend to be polycentric and networked development stage with significant tendency for regional economic integration. In southern China, Guangdong and Guangxi are classified into the same community (Community 2). The PRD has been one of the most developed megaregions with dramatically driving and influencing capacities on the surrounding regions. Guangxi and Guangdong are both located on the south of Nanling Mountains and belong to the Pearl River Basin. They share similarity in the physical geography, historical accumulation and sociocultural context. They have close social and economic relations for a long time and now the Zhujiang-Xijiang economic belt has been proposed as national strategy. In northern China, Beijing, Tianjin, and provinces of Hebei and Shandong are divided into the same group. Beijing and Tianjin, as the nodal cities, have acted as the engines for economic growth within the BTH megaregion; as a result, its economic radiation capacity has spread to the neighboring Shandong Province that finally formed the Beijing, Tianjin, Hebei and Shandong community.

### (3) Core-periphery structure

The division of urban economic regions, based on highway flows, has shown obvious characteristics of administrative region economy and provincial administrative boundaries

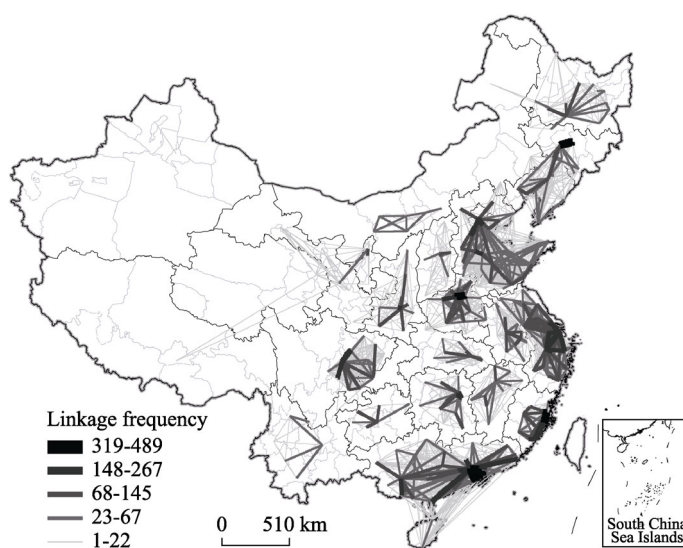


have also acted as important dividing lines within different regions. At the same time, however, it is also clear that some cities located near provincial borders have become disconnected from their own administrative frameworks and have consequently been incorporated into the economic zones of neighboring provinces. For example, the Tongliao city of Inner Mongolia Autonomous Region has close links with Liaoning and Jilin provinces so that they together form Community 9. Similarly, the cities of Chifeng and Anyang, located in the border regions of Inner Mongolia and Henan, respectively, are both divided into the Beijing-Tianjin-Hebei-Shandong community (Community 3); the cities of Fuyang and Bozhou in the northwest of Anhui Province are attracted into the Central Plain economic region (Community 4); the cities of Tianshui, Pingliang, Qingyang, and Longnan in southern Gansu Province all exhibit close connections with the Shaanxi community centered around the city of Xi'an (Community 8); the cities of Chengdu and Chongqing with surrounding small and medium-sized cities are integrated into one group (Community 6); the cities of Baicheng and Songyuan in Jilin Province have deeper connections with neighboring Heilongjiang Province (Community 13); the Panzhihua city as the southernmost city in Sichuan Province is grouped into Yunnan community (Community 18). Indeed, because of their geographical locations and physical surroundings, many cities in provincial border regions usually receive limited economic influence from economic centers in their own provinces and tend to be shadow regions of resource allocation and policy coverage. Therefore, these cities are more easily attracted by powerful economic centers in neighboring provinces and get rid of administrative constraints to amalgamate with adjacent cities and regions.

## 5 Regional network structures and spatial organization

In previous sections, we applied the community detection method to subdivide Chinese prefecture-level administrative units into 19 urban economic regions (or communities). These urban economic regions, as important components of the spatial configuration in Chinese urban system, portray clear spatial patterns of regional city networks from a spatial linkage perspective and help to understand the spatial dependence structures in different territorial systems. We build on these results to further visualize the geographical space and topological properties of individual territorial systems based on the spatial dimensions of urban economic regions (Figure 4).

Overall, each of the communities is characterized by a marked city network system that exhibits strong spatial



**Figure 4** The spatial configuration of China's city networks based on community detection

dependence and various spatial organization patterns. Specifically, the densest communities identified in this research are those that comprise Shanghai-Jiangsu-Zhejiang, Guangdong-Guangxi, and Beijing-Tianjin-Hebei-Shandong, followed by Chengdu-Chongqing, Henan, and Liaoning-Jilin. It is therefore clear that highway flows can be utilized to most effectively illustrate the important role played by spatial distances in regional structures of interactions. Results also reveal that within a single regional system, spatial correlation patterns have often formed with a central city at the core and with intercity connectivity spreading outwards from the central city to the surrounding cities due to the law of distance decay. Thus, from a morphological perspective, the spatial structure of regional city networks can be broadly classified as either monocentric, dual-nuclei, polycentric, or low-level equilibration structures. Most regional city networks in China have developed following a monocentric pattern; this kind of regional development system characterizes Community 3, Community 4, Community 8, Community 11, Community 12, Community 13, Community 14, Community 15, and Community 18, while a dual-nuclei regional system characterizes Community 6 and Community 9, a polycentric regional system characterizes Community 1, Community 2, Community 5, and Community 7, and a regional system with a low-level of equilibrium structure characterizes Community 10, Community 16, and Community 17.

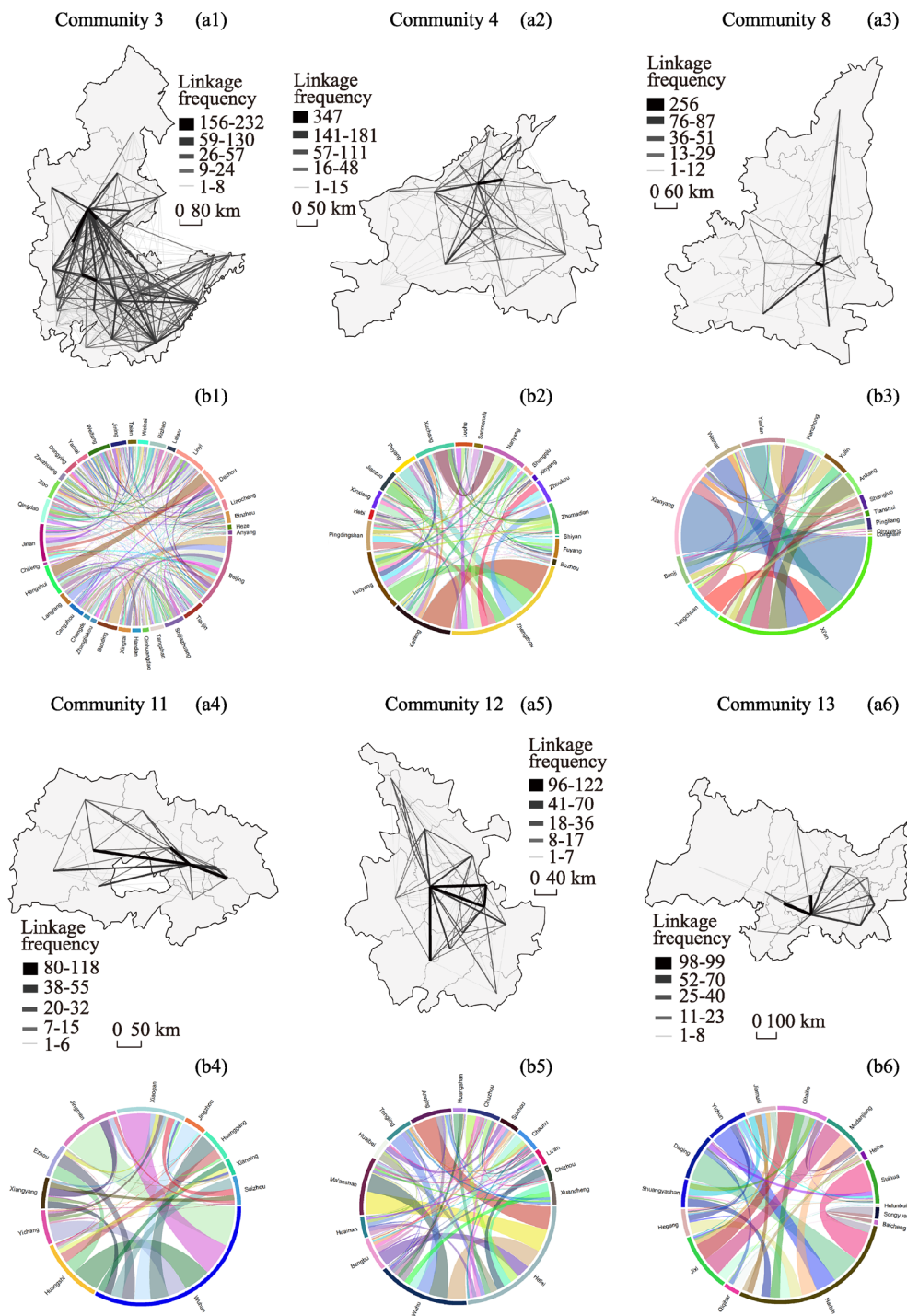
### 5.1 Monocentric development model

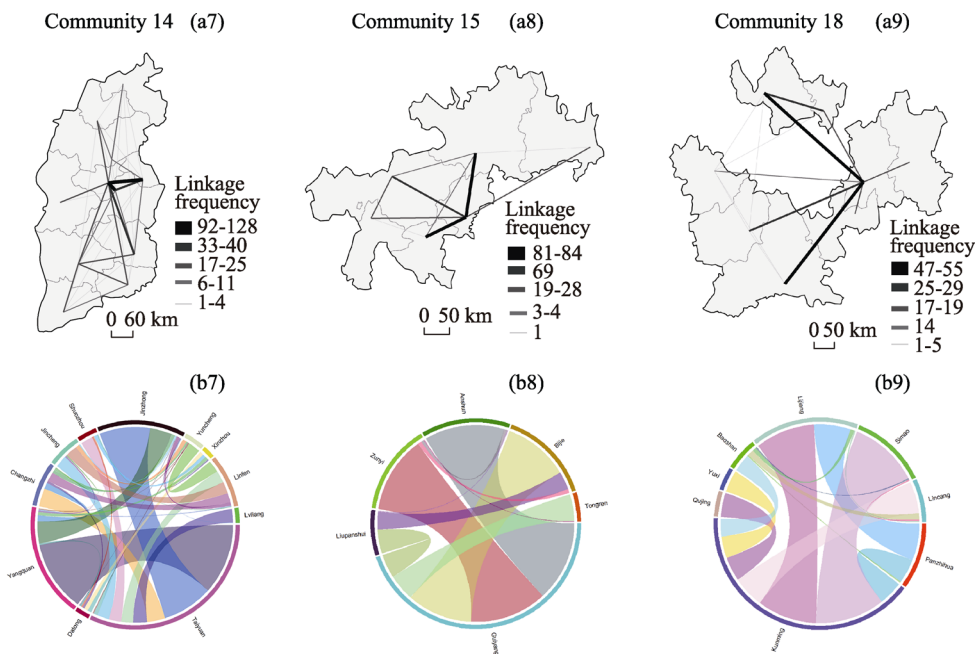
A monocentric regional system often centers on a single large city as its core; this large city is closely connected to adjacent small and medium-sized cities and, the system thus encapsulates a spatial organization pattern of core-periphery structure. Such a monocentric urban system also tends to display rank-size structures and the characteristics of vertical linkage, as the single core city dominates the entire region and surrounding small and medium-sized cities show obviously spatial directivity towards this regional center. Thus, during the initial stage of regional economic development, the regional central city tends to enter the status of agglomeration and expansion, and often has strong siphonic effects on all kinds of resources and policies, such as capital, investment, talent, population, and information. These all lead to varying degrees of spatial polarization. Due to the regional circulation and accumulated effect, increased volumes of high quality resources and development opportunities tend to flow to the core city or larger urban areas and so a monocentric regional structure gradually develops. The monocentric spatial structure is therefore a natural geographic phenomenon alongside the processes of socioeconomic development, which enables both rationality and inevitability in a particular development stage.

From a spatial morphology perspective, regional city networks in China based on highway flows mainly demonstrate monocentric development model, and the spatial structures include radial, ring-shaped, and fan-shaped spatial interaction morphology. In these regions, central cities tend to occupy dominant positions while sub-center cities tend to be under-developed, indicative to a certain extent of current situation of regional economic development in China. Among the 19 communities identified above, nine of the whole communities exhibit monocentric spatial structures to some extent. Detailed results are shown in Figure 5, among which the label (a) represents the geographic network, the label (b) represents the topological network.

5.2 Dual-nuclei development model

A dual-nuclei development model is, as the name implies, a spatial operation mechanism of regional development driven by two central cities. Within a territorial system, the dual-nuclei spatial structure usually comprises two central cities acting as core development





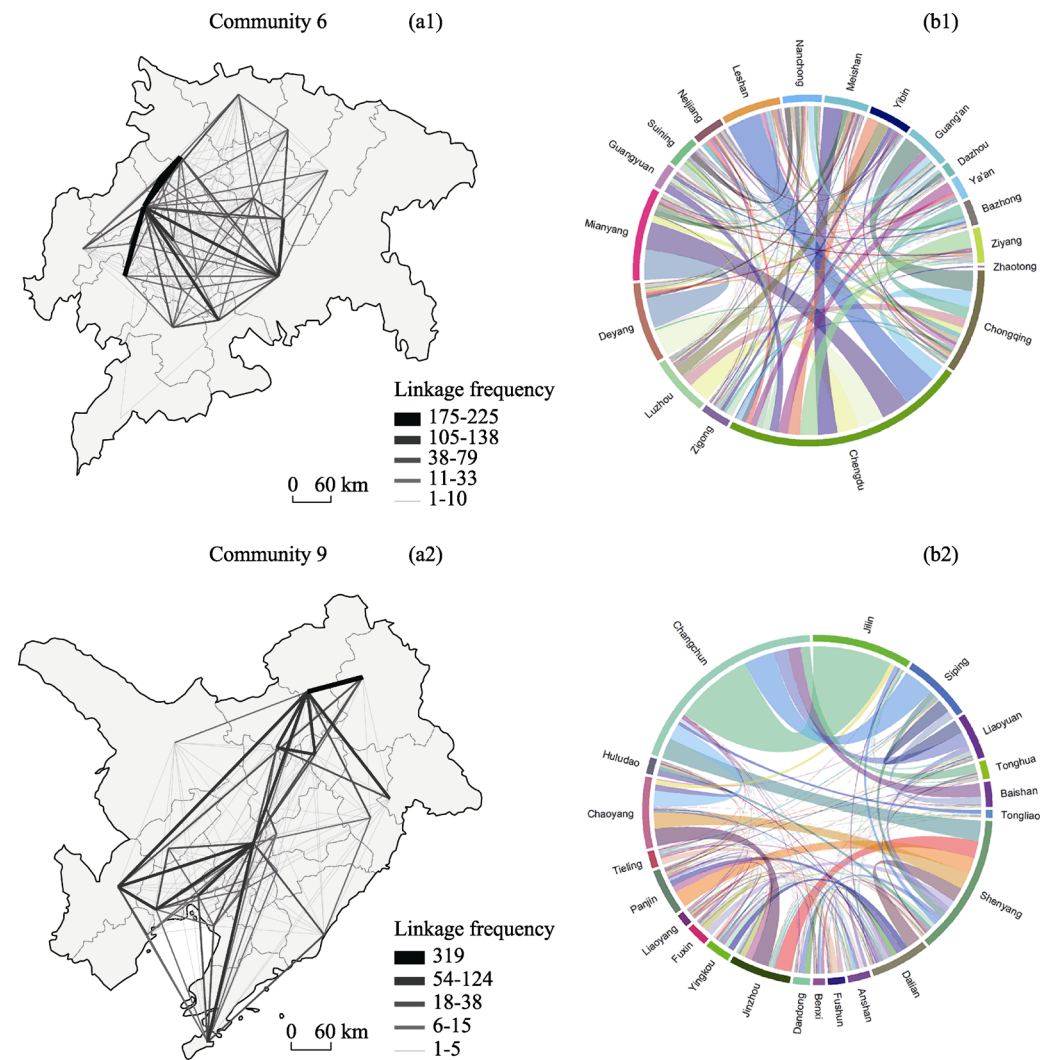
**Figure 5** The spatial organization of regional city networks based on monocentric structures

engines that are closely interconnected with a series of surrounding small and medium-sized cities; taken together, these cities constitute a multi-level, networked urban system. In comparison with monocentric spatial structure, dual-nuclei spatial structure owns its distinguished characteristics. On the one hand, the two central cities are often separated by a certain distance in geographical space and respectively form their own city network systems in individual hinterland. On the other hand, however, these two urban systems often have considerable crossover and overlap that some cities in one urban system also have certain linkages with cities in the other urban system and high-ranking cities tend to be frequently interconnected beyond administrative boundaries. In such a situation, the regional development model driven by “two engines” that integrates rank-size and functional network is likely to take shape.

In China’s regional city networks, both Chengdu-Chongqing region (Community 6) and Liaoning-Jilin region (Community 9) show, to some extent, dual-nuclei development model (Figure 6). In these two communities, the nodal cities respectively develop their own subsystems, and dense connectivity also exists between the subsystems, finally forming relatively typical regional development model driven by “two engines”.

**5.3 Polycentric development model**

Along with socioeconomic development, production factors such as population, industries, and resources tend to constantly concentrate towards central cities. As a result, urban areas and populations of central cities continue to expand, often leading to urban development problems such as urban sprawl, traffic congestion, shortages of housing, and resources and environment deterioration. Previous work has shown that such ‘urban’ or ‘regional diseases’ are more likely to occur in cities and regions that have monocentric spatial structures. Thus, given this background, governments and academic researchers around the world have noted

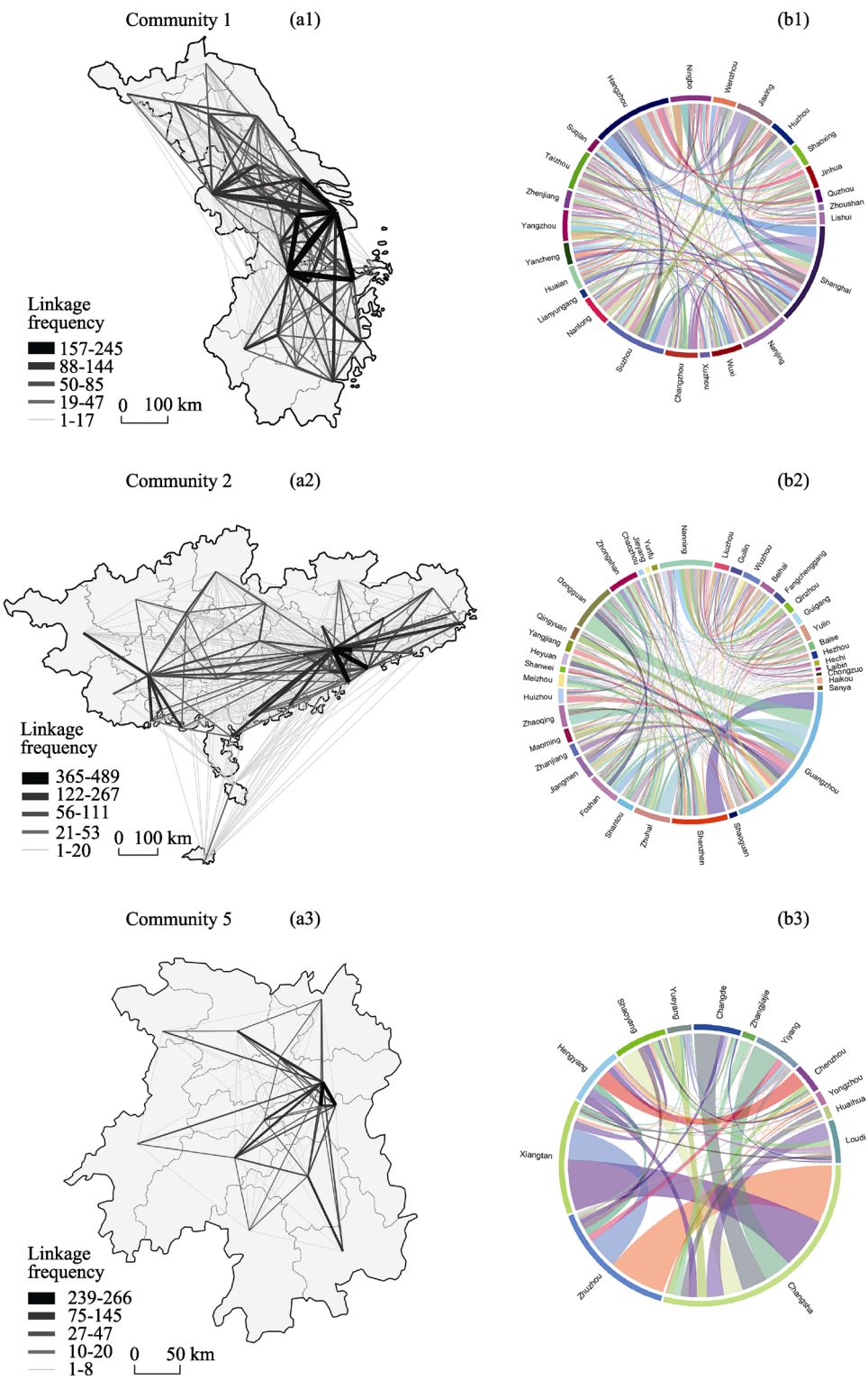


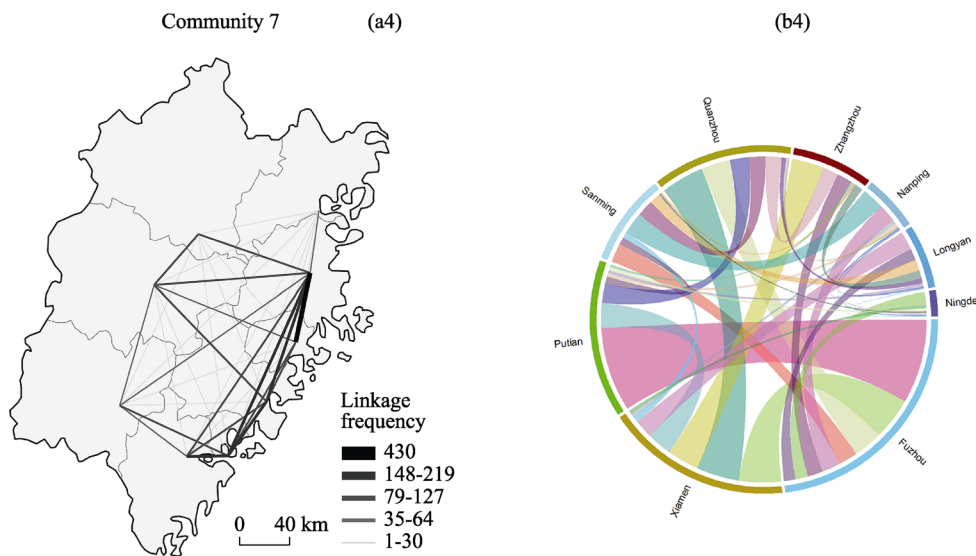
**Figure 6** The spatial organization of regional city networks based on dual-nuclei structures

that a polycentric spatial structure appears to provide a more efficient and stable model for regional development; as a result, this kind of spatial organization of polycentric structure has gradually become more and more critical in the promotion of urban and regional sustainable development. The polycentric spatial structure proposes that the regional economy should be transformed from one that is dominated by administrative divisions to one that is orientated towards relational geographies, and the traditional monocentric spatial structures should be promoted to evolve into new spatial organizational models of regional development that are multi-level, dynamic, and networked.

Generally speaking, the polycentric development model would encompass several central cities as the cores and would rely on well-developed infrastructural networks, forming substantial spatial relationships and functional networks for resource sharing, factor mobility and division cooperation with surrounding small and medium-size cities. In the divided communities, Shanghai-Jiangsu-Zhejiang community (Community 1), Guangdong-Guangxi





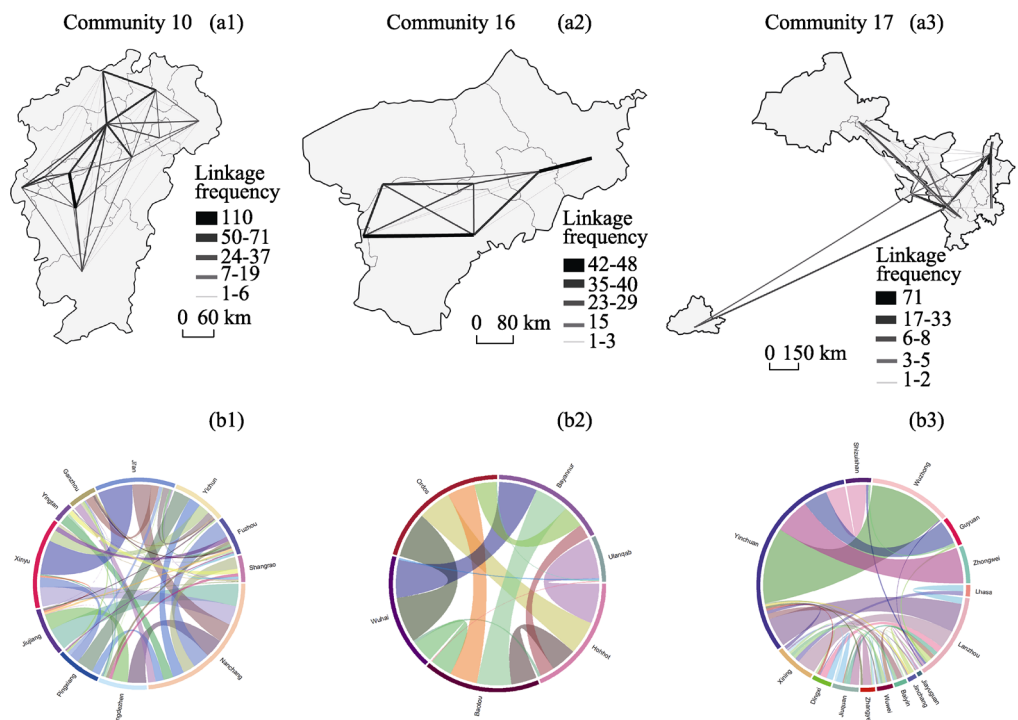


**Figure 7** The spatial organization of regional city networks based on polycentric structures

community (Community 2), Hunan community (Community 5), and Fujian community (Community 7) all conform to varying degrees with a polycentric development model. In terms of spatial morphology, the Shanghai-Jiangsu-Zhejiang community centered on the YRD megaregion and the Guangdong-Guangxi community centered on the PRD megaregion are both characterized by sophisticated polycentric structure developmental morphologies. Similarly, the Hunan community centered on Changsha-Zhuzhou-Xiangtan megaregion and the Fujian community centered on Fuzhou and Xiamen display some characteristics consistent with the early regional development of morphological polycentricity although they remain in a primary stage.

**5.4 Low-level equilibration development model**

Given a specific set of spatiotemporal circumstances, cities within a given region can share similar socioeconomic development characteristics while their socioeconomic activities and linkages in this context remain relatively balanced. As this region has no significant economic centers and growth poles, cities will tend to be characterized by relatively balanced levels and patterns of development. In terms of spatial organization, in addition to monocentric, dual-nuclei, and polycentric structures, the city networks in some communities in this context are also at a low, but balanced, stage of development. No obvious core engines are present within these regions, and they are characterized by small economic scale, slow factor mobility, and limited linkage strength. These regions (or communities) are not balanced and integrated regions driven by the highly-developed regional economy and in fact they are usually under-developed areas. As shown in Figure 8, the Jiangxi region (Community 10), the central and western Inner Mongolia (Community 16), the Gansu-Ningxia-Qinghai-Tibet region (Community 17), and the Xinjiang region (Community 19) all comprise these kinds of regions (Figure 8).



**Figure 8** The spatial organization of regional city networks based on low-level equilibration structures

**6 Conclusions and discussion**

Urban and regional studies utilizing relational data enable new perspectives of more open, dynamic and networked. As a result, the use of multi-perspective and multi-scalar city network has gradually become more and more important as the basis of our understanding of spatial interactions and linkages. Road linkages provide some distinguishing characteristics that reveal spatial dependence and distance decay, and have proven to be of great significance in depicting spatial relationships at the regional scale. Utilizing data on highway passenger flows between prefecture-level administrative units, the aim of this paper was to identify functional structures and regional impacts on city networks in China, and to further explore patterns in the spatial organization of existing functional regions. The results of this study enable a deeper understanding of the structures of city networks and provide a number of new cognitive perspectives for future research. The empirical results are shown as follows.

(1) It is immediately evident that highway flows are markedly concentrated within the megaregions of eastern coastal China and major economic zones in central and western China. And city networks constructed on the basis of highway flow data exhibit strong spatial dependence and hierarchical characteristics, spatially coupled to a large extent with the distribution of major megaregions in China. This trend is therefore more of a reflection of spatial relationships at the regional scale as well as core-periphery structures.

(2) Nineteen communities that belong to an important type of spatial configuration are identified through community detection algorithm, and we suggest they are correspondingly urban economic regions within urban China. Their spatial metaphors can be concluded in three aspects. Firstly, many of these communities share the same boundaries with provin-



cial-level administrative units, demonstrating significant administrative regional economy still exists in contemporary China. Secondly, trans-provincial linkages can be formed though the spatial spillover effects of megaregions within specific communities. Thirdly, cities located in marginal areas of provinces that are attracted by powerful central cities in neighboring provinces, are likely to become increasingly disconnected with their own provinces and be enrolled into communities of neighboring provinces, which contributes to the formation of the trans-provincial core-periphery structures.

(3) Each community can be characterized by a particular city network system, demonstrating strong spatial dependence and various spatial organization patterns. Regional patterns have emerged with the features of multi-level, dynamic, and networked. From the point-of-view of morphology, the spatial structures of regional city networks can basically be divided into monocentric, dual-nuclei, polycentric, and low-level equilibration structures. The majority, however, have developed according to a monocentric pattern.

In contemporary urban geography, both the research directions and spatial scales have been gradually enhanced while the empirical studies of multi-perspective and multi-scalar city networks have significantly deepened the regional cognition of city network development in China. The aim of this paper was therefore to depict the spatial structures and organization patterns of China's city networks using highway passenger flows. The main contribution of this study is its attempt to rectify existing weaknesses inherent to the use of macro-scale highway flow data in the portrayal of regional interrelated structures and spatial organizations, which will broaden the existing research perspective on city network that are subject to strong distance decay and promote a clearer understanding of the roles played by geographical distance and city hierarchy in city network development. Nevertheless, taking into account the inaccessibility of real traffic flows, the bus schedule data used in this study is necessarily a type of parameter substitution to real flow data. Due to the limitations of data sources and web crawling techniques, this research neglects the spillover effect of actual schedules caused by "station stops along the road networks" in real highway passenger transportation. Meanwhile, we were unable to obtain highway flow data at finer scales and it will be of great value to the identification of regional structures and interconnected patterns of city networks at the county-level scale. Research on multi-scalar city network is continuously deepening the fundamental urban system theory, enabling a range of new perspectives and theoretical cognition for spatial relationships at different spatial scales, which is also an important development direction in future urban studies.

## References

- Alderson A S, Beckfield J, 2004. Power and position in the world city system. *American Journal of Sociology*, 109(4): 811–851.
- Beaverstock J V, Smith J, 1996. Lending jobs to global cities: Skilled international labour migration, investment banking and the city of London. *Urban Studies*, 33(8): 1377–1394.
- Blondel V D, Guillaume J L, Lambiotte R *et al.*, 2008. Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment*, 2008(10): P10008.
- Camagni R, Capello R, 2004. The city network paradigm: Theory and empirical evidence. In: Capello R, Nijkamp P (eds). *Urban Dynamics and Growth: Advances in Urban Economics*. Amsterdam: Elsevier.
- Castells M, 2010. Globalisation, networking, urbanisation: Reflections on the spatial dynamics of the information age. *Urban Studies*, 47(13): 2737–2745.

- Chen W, Xiu C L, Ke W Q *et al.*, 2015. Hierarchical structures of China's city network from the perspective of multiple traffic flows. *Geographical Research*, 34(11): 2073–2083. (in Chinese)
- Clauset A, Newman M E J, Moore C, 2004. Finding community structure in very large networks. *Physical Review E*, 70(6): 066111.
- Csardi G, Nepusz T, 2006. The igraph software package for complex network research. *InterJournal, Complex Systems*, 1695(5): 1–9.
- Derudder B, Taylor P J, Hoyler M *et al.*, 2013. Measurement and interpretation of connectivity of Chinese cities in world city network, 2010. *Chinese Geographical Science*, 23(3): 261–273.
- Derudder B, Witlox F, 2008. Mapping world city networks through airline flows: Context, relevance, and problems. *Journal of Transport Geography*, 16(5): 305–312.
- Dong C, Xiu C L, Wei Y, 2014. Network structure of 'space of flows' in Jilin Province based on telecommunication flows. *Acta Geographica Sinica*, 69(4): 510–519. (in Chinese)
- Girvan M, Newman M E J, 2002. Community structure in social and biological networks. *Proceedings of the National Academy of Sciences*, 99(12): 7821–7826.
- Gu C L, 1991. A preliminary study on the division of urban economic regions in China. *Acta Geographica Sinica*, 46(2): 129–141. (in Chinese)
- Hall P, Pain K, 2006. *The Polycentric Metropolis: Learning from Mega-city Regions in Europe*. London: Earthscan.
- Harrison J, Hoyler M, 2015. *Megaregions: Globalization's New Urban Form?* Cheltenham: Edward Elgar.
- Hoyler M, Kloosterman R C, Sokol M, 2008. Polycentric puzzles-emerging mega-city regions seen through the lens of advanced producer services. *Regional Studies*, 42(8): 1055–1064.
- Lancichinetti A, Fortunato S, 2009. Community detection algorithms: A comparative analysis. *Physical Review E*, 80(5): 056117.
- Liu W D, Zhen F, 2004. Spatial implications of new information and communication technologies. *Acta Geographica Sinica*, 59(S1): 67–76. (in Chinese)
- Malecki E J, 2002. The economic geography of the Internet's infrastructure. *Economic Geography*, 78(4): 399–424.
- Pons P, Latapy M, 2006. Computing communities in large networks using random walks. *Journal of Graph Algorithms and Applications*, 10(2): 191–218.
- Raghavan U N, Albert R, Kumara S, 2007. Near linear time algorithm to detect community structures in large-scale networks. *Physical Review E*, 76(3): 036106.
- Rosvall M, Bergstrom C T, 2008. Maps of random walks on complex networks reveal community structure. *Proceedings of the National Academy of Sciences*, 105(4): 1118–1123.
- Taylor P J, 2001. Specification of the world city network. *Geographical Analysis*, 33(2): 181–194.
- Taylor P J, 2004. The new geography of global civil society: NGOs in the world city network. *Globalizations*, 1(2): 265–277.
- Taylor P J, Catalano G, Walker D R F, 2002. Measurement of the world city network. *Urban Studies*, 39(13): 2367–2376.
- Taylor P J, Evans D M, Hoyler M *et al.*, 2009. The UK space economy as practised by advanced producer service firms: Identifying two distinctive polycentric city-regional processes in contemporary Britain. *International Journal of Urban and Regional Research*, 33(3): 700–718.
- Taylor P J, Hoyler M, Verbruggen R, 2010. External urban relational process: Introducing central flow theory to complement central place theory. *Urban Studies*, 47(13): 2803–2818.
- Yu T F, Gu C L, Li Z G, 2008. China's urban systems in terms of air passenger and cargo flows since 1995. *Geographical Research*, 27(6): 1407–1418. (in Chinese)
- Zhao M, Wu K, Liu X *et al.*, 2015. A novel method for approximating intercity networks: An empirical comparison for validating the city networks in two Chinese city-regions. *Journal of Geographical Sciences*, 25(3): 337–354.
- Zhen F, Wang B, Chen Y, 2016. Research on China's city network based on users' friend relationships in online social networks: A case study of Sina Weibo. *GeoJournal*, 81(6): 937–946.
- Zhong C, Arisona S M, Huang X *et al.*, 2014. Detecting the dynamics of urban structure through spatial network analysis. *International Journal of Geographical Information Science*, 28(11): 2178–2199.
- Zhong Y X, Lu Y Q, 2011. Hierarchical structure and distribution pattern of Chinese urban system based on railway network. *Geographical Research*, 30(5): 785–794. (in Chinese)
- Zhou Y X, Zhang L, 2003. China's urban economic region in the open context. *Acta Geographica Sinica*, 58(2): 271–284. (in Chinese)