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RESEARCH ARTICLE

Spatiotemporal dynamics of the urban sprawl in a typical urban agglomeration: a case study on Southern Jiangsu, China (1983–2007)

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Abstract China has experienced urbanization at an unprecedented rate over the past decades. Against this background, this paper demonstrates the multi-level spatiotemporal urban sprawl process from 1983 to 2007 on the perspective of urban agglomeration with a case study in Southern Jiangsu. Based on a combination of eight rounds of satellite images from 1983 to 2007, the presented results suggest the following three main findings: (1) At the prefecture-city level, the urban sprawl in Southern Jiangsu has presented significantly divergent growth patterns, with more than half of this vast growth occurring in the Suzhou prefecture-level city. (2) At the county level, clear spatial differentiations exist in the direction of the urban sprawl. The centroids of all county seats in the Suzhou and Wuxi prefecture-level cities have an eastward tendency (Shanghai oriented), while those of the county seats in the Changzhou prefecture-level city tend to be westward (Nanjing oriented). (3) At the township level, two convergent groups have gradually formed over time; namely, the low density urban zone in the western hilly land and the high density urban zone around the three central downtown areas. The urban areas close to urban cores tend to merge, showing a high-density convergent growth pattern, as do the western and southwestern townships in Southern Jiangsu, showing a low-density convergent growth pattern. All of these findings may be valuable for researchers and local authorities in providing reference for regional coordinated growth, environmental management, and urban planning decision-making.

Keywords Southern Jiangsu, urban sprawl, spatiotemporal dynamics, rapid urbanization areas

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1 Introduction

As the largest developing country in the world, China has entered into an unprecedented urbanization stage since the launch of reform and open policy in the late 1970s (Anderson and Ge, 2005). In 1978, there were merely 193 cities nationwide. However, by 2010, this number had risen more than threefold to 661. Meanwhile, the country's urban population grew four-fold from 172 million to 670 million over the same period, resulting in the formation of numerous, large urban agglomerations in regions such as the Yangtze River Delta, Pearl River Delta, and Jing-Jin-Tang (in Beijing, Tianjin, and Tangshan, respectively) (Zhou and Wei, 2011). In contemporary China, urban agglomeration's magnetic attraction for investment led to the development of industrial and service sectors, employment generation, migration, and population growth. An increased understanding of the characteristic process and evolutionary trend of urban sprawl on urban agglomerations is crucial to regional economic and social sustainable development. However, the majority of research conducted in China mainly focuses on single large-cities, such as Beijing, Shanghai, Guangzhou, Shenzhen, and etc. (Wang et al., 2007; Yu and Ng, 2007; Wu, 2008; Fan et al., 2009; Luo and Wei, 2009; Gong et al., 2011; Li et al., 2011; Liu et al., 2012; Kong et al., 2012; Shi et al., 2012), leaving a knowledge gap on the perspective of urban agglomeration. Urban agglomeration as an aggregation of multi-level cities with varied characteristics and function in a given region; its own development definitely contributes to the synergistic development of internal cities. Hence, multi-level urban sprawl analyses (prefecture city-county-township) need to be integrated for a better understanding of the urban sprawl in a given urban agglomeration.

Remote sensing (RS) provides spatially consistent image information covering broad areas, and offering both high spatial resolution and high temporal frequency (Weng, 2012); hence, this technique has been widely used to monitor urban sprawl (Miller and Small, 2003; Huang et al., 2007; Jat et al., 2008; Bhatta et al., 2010a; Taubenböck et al., 2012). This study applies multi-temporal remote sensing analysis, spatial analysis, and spatial autocorrelation analysis to demonstrate the spatiotemporal urban sprawl process on the perspective of urban agglomeration. Specifically, we examine a case study in a typical megalopolitan region of the country, namely Southern Jiangsu. The remainder of this article is organized as follows. The second section introduces the study area and datasets. The third section proposes the methods for analyzing urban sprawl. The spatiotemporal features of urban sprawl at multi-levels in Southern Jiangsu are illustrated in section four, and the driving factors are discussed in the fifth section.

2 Study area and datasets

2.1 Study area

Southern Jiangsu is comprised of three prefecture-level cities — Suzhou, Wuxi, and Changzhou (Fig. 1), covering 17,516 km^2 with a population of 21.8 million. Sparsely-distributed hills cover the area west of Southern Jiangsu, while Tai Lake Plain covers the eastern and central areas, characterized by low, flat terrain and home to the third largest lake in China, Tai Lake, as well as the longest river, Yangtze River. During China's reform and opening up over the past 35 years, Southern Jiangsu's economic development has been specifically summarized as the "Southern Jiangsu pattern", one of three templates for development in contemporary China along with the "Wenzhou pattern" and the "Pearl River Delta pattern" (Wei, 2002). The "Southern Jiangsu pattern" is characterized by a "vibrant township, collective economy, strong local government intervention, and fast non-agricultural processes" (Shen and Ma, 2005). Since 1998, the former "Southern Jiangsu pattern" has evolved into the "new Southern Jiangsu pattern," characterized by "attracting foreign investment, activating private capital, and enhancing the export-oriented economy" (Wei, 2010).

The history of the urban development experienced in Southern Jiangsu is of great research interest for three reasons. First, Southern Jiangsu is the most developed region in China. In 2010, it constituted approximately 0.18% of China's land, yet accounted for over 4.5% of national GDP. Second, Southern Jiangsu is representative

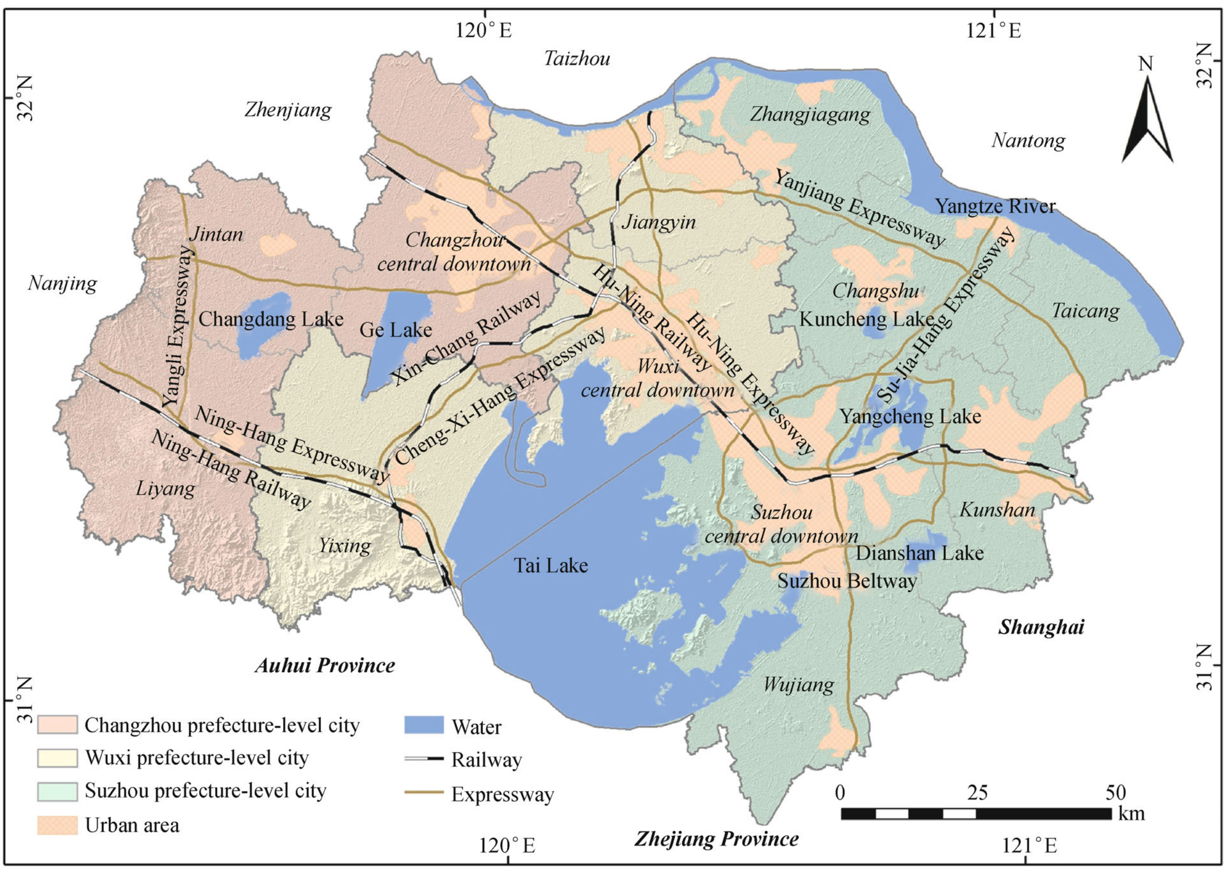

Fig. 1 Location of the study area: the Southern Jiangsu administrative map.

of regional development in contemporary China. Its urbanization process is similar to those of many other urban agglomerations in terms of developing an export-oriented economy, welcoming surges of migrant workers, and undergoing drastic urban expansion. Third, most studies on this topic are carried out in developed, newly industrialized countries (Masek et al., 2000; Overman and Ioannides, 2001; Black and Henderson, 2003; Herold et al., 2003; Nechyba and Walsh, 2004; Bosker et al., 2008; Catalan et al., 2008; Apparicio et al., 2009; Klaufus, 2010; Boarnet et al., 2011; Bagan and Yamagata, 2012). This study thus provides a comparable case in a less developed nation.

The definitions of "urban area" differ by country (Ma et al., 2008; Bhatta et al., 2010b). In this study, urban area is defined as a collection of contiguous urban land, such as urban settlements, industrial land, commercial land, and warehouse land. This area is also comprised of the following types of land cover: 1) open spaces (such as greenbelt, bodies of water, and rivers) surrounded by urban land; 2) industrial zones or parks adjacent to urban land; and 3) rural settlements adjacent to urban land. There are three administrative levels in Southern Jiangsu's urban system: prefecture-level cities, county-level cities, and townships. Herein, "cities" correspond to local administrative and jurisdictional entities rather than to urban areas. In practical terms, urban areas in the study area include three central downtown areas, nine county seats, and 274 town seats. It is important to note that each central downtown areas is composed of several urban areas from different district seats that merge together and can be difficult to distinguish from satellite images. Hence, all the central downtown areas of the three investigated prefecture-level cities were treated as three individual analytical units. The urban sprawl of Southern Jiangsu is reflected in the change of urban areas in each prefecture-level city, in the expansion direction of the county center, and in the spatial correlation of townships; therefore, it is our goal to analyze the internal differences at multiple levels (including prefectural city-county-township level) to grasp the essence of urban sprawl.

2.2 Datasets

Eight samples (1983, 1991, 1995, 1999, 2001, 2003, 2005, and 2007) of Landsat MSS, TM, and ETM+ images (Table 1) were collected in order to extract the urban areas in Southern Jiangsu. Unequal time intervals were mainly due to data limitations and overlaps with the developmental stages in China. We selected eight-year intervals for the initial stages of China's reform and opening up (1983–1991; i.e., before Deng Xiaoping's South Tour Speeches), four-year intervals for the reinvigorated reform process period (1991–1999; i.e., before China's accession to the World Trade Organization in 2001), and two-year intervals from 1999 to 2007.

In addition, 1∶50,000 topographic maps of the study area were collected to facilitate the geo-correction of these satellite images, while we used land-use maps (1∶50,000 scale) from 2005 to validate the accuracy of the extracted urban areas. Digital elevation models of Southern Jiangsu were also collected for topographic analysis. Moreover, socio-economic statistical data on the three prefecture-level cities including the variables of GDP, urban population, and floating population, were collected for the factor analysis.

3 Methods

3.1 Urban area extraction

Precise geometric registration to a common map reference and co-registration between individual images are crucial for ensuring the reliable detection of temporal changes in urban areas. All satellite images were thus geometrically corrected to a uniform map reference system — the Universal Transverse Mercator north 51st zone projection system (UTM 51N) with the World Geodetic System datum (WGS-84) — using a different number (approximately 28–32) of ground control points for each image. The total root mean square error was no more than 0.5 pixels for each image. The spatial resolution of TM and ETM+ images was 30 m for bands 1–5 and 7. The spatial resolution of MSS images was approximately 79 m, but these data were resampled to 80 m using the cubic convolution method. Other pre-processing, including study area selection and image mosaics, was carried out for the satellite images. In this study, the urban areas in Southern Jiangsu were extracted by the following two steps.

Table 1 Summary of the satellite images used in this study

Year	Sensors	Date	Path/row	Year	Sensors	Date	Path/row
1983	Landsat-4 MSS	1983-11-14	119/038	2001	Landsat-7 ETM+	2001-07-26	119/038
	Landsat-4 MSS	1983-08-01	120/038		Landsat-7 ETM+	2001-07-17	120/038
1991	Landsat-5 TM	1991-07-23	119/038	2003	Landsat-5 TM	2003-10-28	119/038
	Landsat-5 TM	1991-08-31	120/038		Landsat-5 TM	2003-10-19	120/038
1995	Landsat-5 TM	1995-08-03	119/038	2005	Landsat-5 TM	2005-10-17	119/038
	Landsat-5 TM	1995-10-13	120/038		Landsat-5 TM	2005-10-24	120/038
1999	Landsat-7 ETM+	1999-09-23	119/038	2007	Landsat-5 TM	2007-07-19	119/038
	Landsat-7 ETM+	1999-12-19	120/038		Landsat-5 TM	2007-07-26	120/038

3.1.1 Built-up area extraction (built-ups hereafter)

Three new indices from the five bands of Landsat TM/ETM+ images (i.e., TM_2, TM_3, TM_4, TM_5, and TM_7) were put forward and combined to extract built-ups. These three indices were: (1) the Modified Built-up Index (MBI, Eq. (1)) to enhance the contrast between built-ups and other land covers, (2) the Built-up and Quarry Discrimination Index (BQDI, Eq. (2)) to discriminate between built-ups and quarries, and (3) the Modified Normalized Difference Water Index (MNDWI, Eq. (3)) to enhance the contrast between built-ups and bodies of water. Through visual estimation, the built-ups in the new images were greatly enhanced and well-distinguished from bodies of water, vegetation, quarries, and other land covers. Supervised classification based on the maximum likelihood method was then used to extract built-ups in a given phase.

$$\mathrm{MBI} = \frac{\mathrm{TM}_5 \times \mathrm{TM}_3 - \mathrm{TM}_4^2}{\mathrm{TM}_3 + \mathrm{TM}_4 + \mathrm{TM}_5}, \tag{1}$$

$$\mathrm{BQDI} = \mathrm{TM}_5 - \mathrm{TM}_7, \tag{2}$$

$$\mathrm{MNDWI} = \frac{\mathrm{TM}_2 - \mathrm{TM}_5}{\mathrm{TM}_2 + \mathrm{TM}_5}. \tag{3}$$

3.1.2 Urban area selection

Other built-ups (e.g., rural settlements, roads, and factories far from urban areas) have similar spectral features to urban areas. According to the above-mentioned definition, the urban areas of the three central downtown areas, nine county seats, and 274 town seats, from 1983 to 2007, were selected through visual interpretation. Moreover, the extraction results were post-processed by morphological filtering based on mathematical morphology technology in order to fill inner holes, eliminate pepper noises, and smooth urban edges.

3.2 Centroid analysis

Urban sprawl is an aggregation and radiation process comprised of various elements. In a sense, each central downtown or county seat can be treated as a point with the centroid of each central downtown or county seat is then used to simulate the "point" and to ascertain the direction in which urban expansion is oriented. For example, the centroid (x_i, y_i) of a county seat (i) can be calculated using the image moment method (Teh and Chin, 1988). Eq. (4) is the central moment for order $(p+q)$, $x_{(i,j)}$ and $y_{(i,j)}$ denote the latitude and longitude of the raster center, m and n are rows and columns of the image, while $f(i,j)$ is raster value at locations (i,j). For a binary image (urban area takes the value of 1 and 0 for other land covers), the centroid can be represented by the central moment for order $(1+1)$, $x_{(i,j)}$ is equal to M_{10}/M_{00}, while $y_{(i,j)}$ is equal to M_{01}/M_{00}.

$$M_{pq} = \sum_{i=1}^{m}\sum_{j=1}^{n} x_{(i,j)}py_{(i,j)}qf(i,j). \tag{4}$$

3.3 Spatial autocorrelation analysis

Given the well-developed transportation in Southern Jiangsu, there will always be a connection between non-neighboring units due to the influence of a dense transportation network. Hence, to better explore the spatial pattern of various geographic units, a non-binary adjacent matrix is adopted for analysis.

3.3.1 Distance calculation

Two cases are analyzed as follows: (1) Distance of geographically adjacent units where euclidean distance between the centroids of two geographical units is used in the study. (2) Distance of transportation accessibility, with geographically nonadjacent units—the main types of transportation include railway, expressway, and national, provincial, road, and county roads. We achieve the shortest distance of these two units for all types of transportation networks by using the shortest path analysis method. If two units can be reached through the use of more than one type, then its distance is defined in Eq. (5), where D is the distance of two units, d_i is the distance through transit type i, and w_i is the weight of transit type i. The type of transportation with the corresponding weights is assigned by taking into account the variances in traffic capacity with the different types of transportation, and their varied impact on urban sprawl. The usage of the Delphi method to define the weight and the values for weights respectively, are railway (0.30), expressway (0.25), the national road (0.20), provincial road (0.15), and county road (0.10).

$$D = \frac{\sum_{i=1}^{n} w_i d_i}{\sum_{i=1}^{n} w_i}. \tag{5}$$

3.3.2 Spatial adjacency matrix construction

Based on Tobler's First Law of Geography, all attribute values on a geographic surface are related to each other, but closer values are more strongly related than are more distant ones. Therefore, $w(i, j)$ (i.e., the element of adjacency matrix) is defined as inverse square of the distance between geographical units i and j. In Eq. (6), $D(i, j)$ is the distance of two geographical units. Row standardization for adjacency matrix is conducted in order to eliminate the distribution divergence of elements using Eq. (7), where $w'(i,j)$ is the weight after row standardization.

$$w(i,j) = \frac{1}{D^2(i,j)}, \tag{6}$$

$$w'(i,j) = \frac{w(i,j)}{\sum_{j=1}^{n} w(i,j)}. \tag{7}$$

3.3.3 Global spatial autocorrelation analysis

Global spatial autocorrelation explores the spatial features of the property values in the study area, describes the correlative degree between spatial objects in the area, and determines any prominent spatial distribution patterns. A common global spatial autocorrelation statistic is *Globe Moran's I* (Eq. (8)) (Moran, 1948). In Eq. (8), N is the number of observations, while x_i and x_j denote the observed value at locations i and j. In this research, x is the distribution density of urban areas, and $x_i = \frac{U_i}{A_i}$, where U is the area of the county urban land, A is the total area of the county. $W(i, j)$ is a spatial weight matrix ($N \times N$), denoting whether i and j are adjacent (1 means yes, 0 otherwise). $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$ is the average of observed values and $S_0 = \sum_{i=1}^{N}\sum_{j=1}^{N} W(i,j)$ the sum of all the elements from $W(i, j)$. Generally, I is interpreted as a correlation coefficient that ranges from -1 to 1. Its expectation is $-\frac{1}{n-1}$. When I is 1, it means that a strong positive spatial autocorrelation exists; when I is -1, a strong negative spatial autocorrelation can be found and spatial difference reaches its maximum. However, when I approaches 0, it means that there is no spatial autocorrelation (i.e., that observations are randomly distributed) (Ma et al., 2008).

$$I = \frac{N}{S_0} \cdot \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W(i,j)(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{N}(x_i - \bar{x})^2}. \tag{8}$$

3.3.4 Local spatial autocorrelation analysis

Global spatial autocorrelation presupposes spatial homogeneity; however, the spatial autocorrelations of all local sections within the study area are rarely the same. Instead, there exists some degree of spatial autocorrelation, as shown by the Local Indicators of Spatial Association (LISA) (Anselin, 1995). These autocorrelations are usually indicated by the index of *Local Moran's I*. In Eq. (9), $S_3 = \frac{\sum_{j=1, j\neq i}^{n} x_j^2}{n-1} - \bar{x}^2$. x_i, $\bar{x}$, and $W(i,j)$ have the same meaning as in Eq. (8).

$$I_i = \frac{x_i - \bar{x}}{S_3}\sum_{j=1}^{N} W(i,j)(x_j - \bar{x}). \tag{9}$$

With *Local Moran' I* and its standardized observation $Z_i \left(Z_i = \frac{I_i - E(I_i)}{\sqrt{\mathrm{Var}(I_i)}} \right)$, the spatial association relations of observations after significance testing ($p = 0.05$) can be assessed:

1) High-high relation (H-H): $I_i > 0$ and $Z_i > 0$, indicating that the observation value at both location I and its neighbors are higher than the regional average;

2) Low-low relation (L-L): $I_i > 0$ and $Z_i < 0$, indicating that the observation value at both location I and its neighbors are lower than the regional average;

3) High-low relation (H-L): $I_i < 0$ and $Z_i > 0$, indicating that the observation value at location I is higher than the regional average, while those of its neighbors are lower;

4) Low-high relation (L-H): $I_i < 0$ and $Z_i < 0$, indicating that the observation value at location I is lower than the regional average, while those of its neighbors are higher.

4 Results

4.1 Urban sprawl trends in Southern Jiangsu

The validation results show that the user accuracy of the extraction method (i.e., based on the 2005 land-use maps of Southern Jiangsu) is 88.1%, while the producer accuracy is 86.7%, the overall accuracy is 87.7%, and the kappa coefficient is 0.89. Minor discrepancies in accuracy are mainly due to the borders between urban and rural areas.

Since 1983, urbanization in Southern Jiangsu has consistently increased, both rapidly and conspicuously (Fig. 2). For example, the urban area of Southern Jiangsu changed from just 182.51 km^2 in 1983 to 3,343.83 km^2 in 2007 (Fig. 3(a)). Although the urban areas of the three investigated prefecture-level cities (Suzhou, Wuxi, and Changzhou) were similar in 1983 (70.63 km^2, 66.93 km^2, and 44.95 km^2, respectively), by 2007 Suzhou had grown to 1,750.80 km^2, which was larger than the sum of Wuxi and Changzhou (995.12 km^2 and 597.92 km^2, respectively) (Fig. 3(a)). Further, the annual urban growth rate of

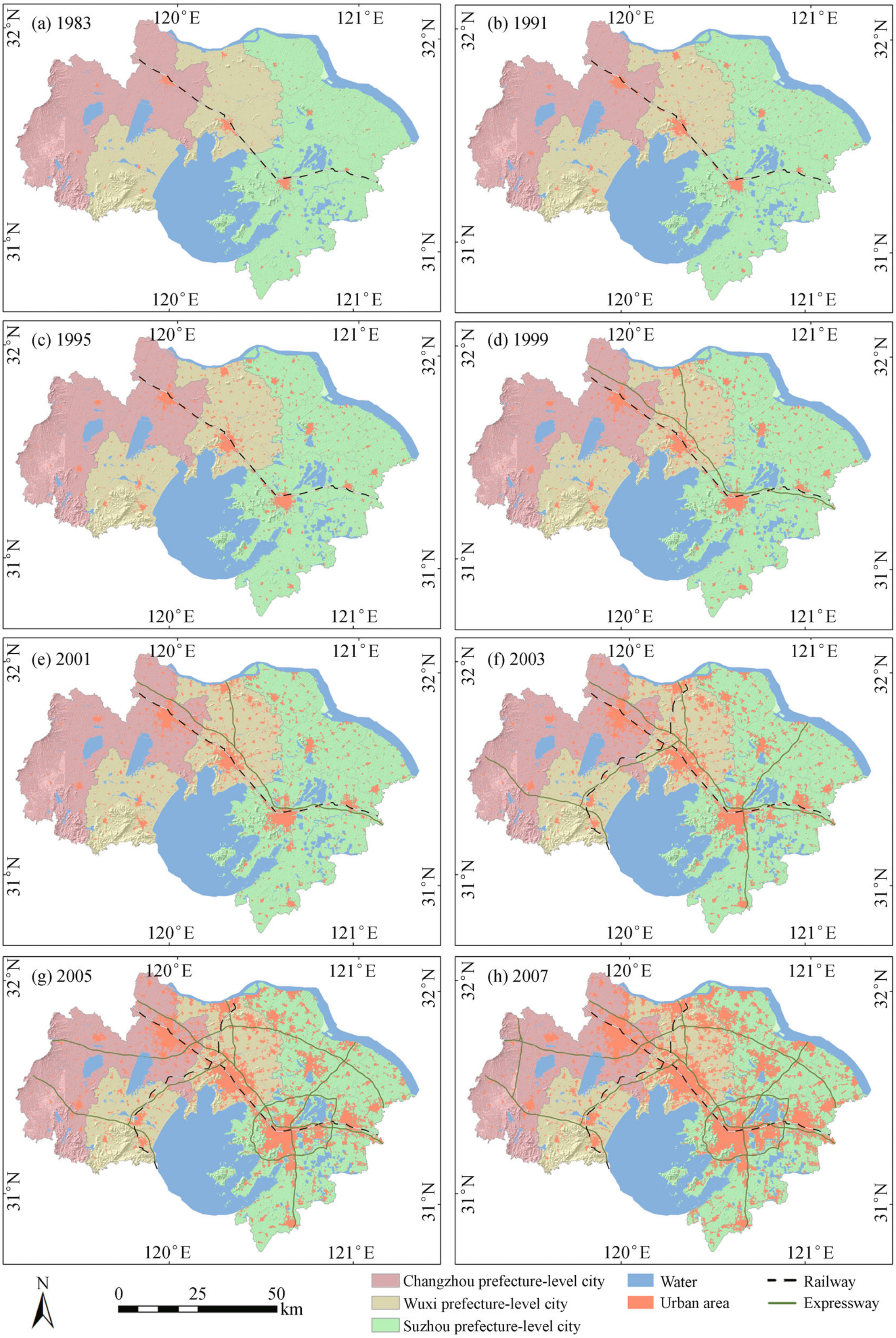

Fig. 2 Results of the extraction of urban areas in Southern Jiangsu from 1983 to 2007.

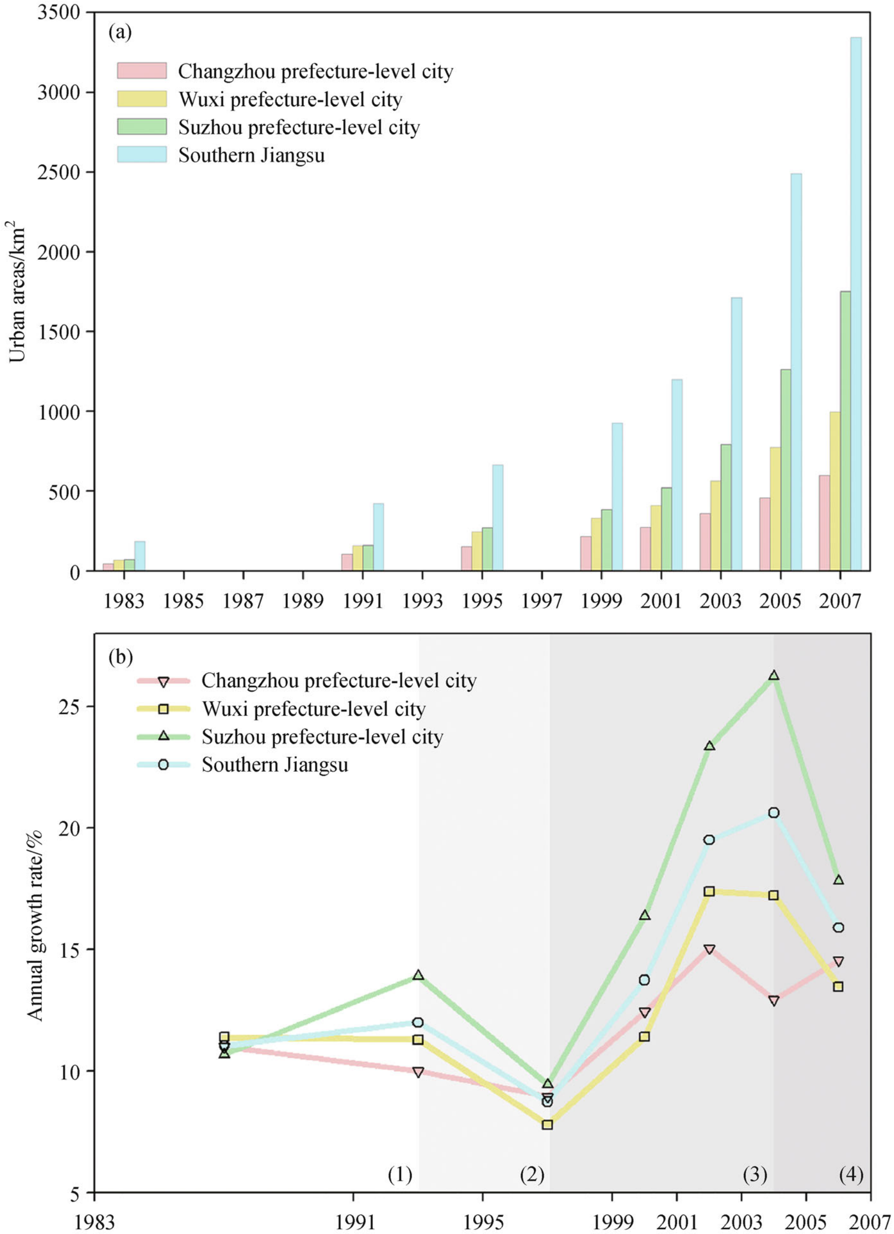

Fig. 3 Urban areas and the urban growth rate in Southern Jiangsu: (a) urban areas of Suzhou, Wuxi, and Changzhou in the eight samples from 1983 to 2007, and (b) annual urban growth rate of Suzhou, Wuxi, and Changzhou from 1983 to 2007.

Southern Jiangsu from 1983 to 2007 was 12.88 (14.31%, 11.90%, and 11.39% for Suzhou, Wuxi, and Changzhou, respectively). In particular, the urban growth rate of Suzhou for each period was above the Southern Jiangsu average (Fig. 3(b)).

In terms of the town seat numbers in the largest 100 urban areas of Southern Jiangsu, Suzhou gradually increased from 31 town seats in 1983 to 56 in 2007, while during the same time period, the town seat numbers decreased from 40 to 30 in Wuxi and from 29 to 14 in Changzhou (Fig. 4). These changes may reflect the influence of proximity to Shanghai. The closer the city is to Shanghai, the faster its urban sprawl rate.

4.2 Spatiotemporal process of urban sprawl at the county level

The centroids of the three central downtown areas and nine county seats from 1983 to 2007 were also calculated. Figures 5(a)–(l) present the spatiotemporal trajectories of the 12 centroids by period, while Fig. 5(m) shows the two main tendencies of these 12 centroids. Overall, nine centroids of all county-level cities in the eastern prefecture-level cities (Suzhou and Wuxi) tend eastward (i.e., in the

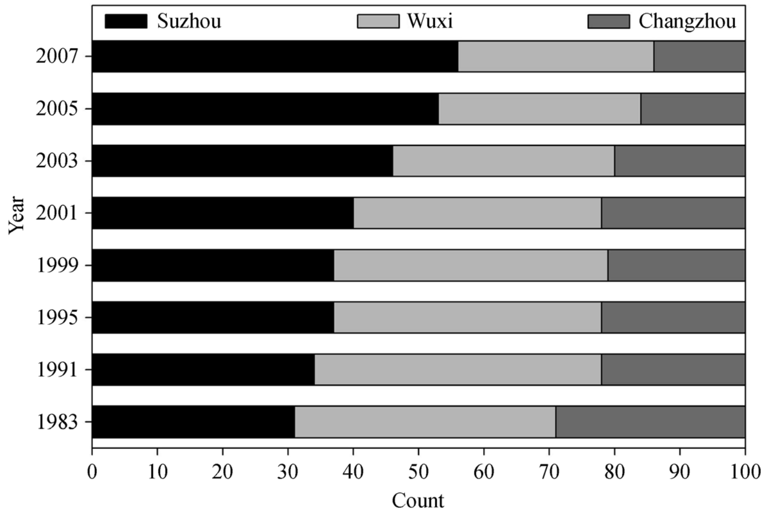

Fig. 4 The number of town seats in Suzhou, Wuxi, and Changzhou in the 100 largest urban areas of Southern Jiangsu in the eight samples from 1983 to 2007.

direction of Shanghai), which again confirms the centripetal effect of the Shanghai metropolis. Specifically, the centroids of the county seats in central Suzhou (including Suzhou central downtown area and the Changshu and Kunshan county seats) tend eastward, the Zhangjiagang county seat centroid tends southeastward, and the centroids of the Wujiang and Taicang county seats tend northeastward. In terms of Wuxi, the centroid of Wuxi's central downtown area tends northeastward, Jiangyin's centroid in north Wuxi tends southeastward, and Yixing's centroid in south Wuxi tends northeastward. Second, the three centroids of all the county-level cities in Changzhou tend westward, which shows susceptibility to the pull of Nanjing, the capital of Jiangsu Province. Finally, in each inner prefecture-level city, the centroids of the county-level cities show a trend towards the central downtown area. For instance, the centroid of Wujiang tends to be toward Suzhou's central downtown, Yixing's centroid tends to be toward Wuxi's central downtown, and Jintan's centroid tends be toward Changzhou's central downtown.

4.3 Spatiotemporal process of urban sprawl at the township level

Global Moran's I was used to reflect the spatial convergence of the investigated urban areas. Figures 6 (a)–(h) are scatter diagrams of *Global Moran's I* based on the 274 townships in Southern Jiangsu; the horizontal axis indicates the distribution densities of urban areas and the vertical axis the spatial lags of these densities. The first and third quadrants of these scatter diagrams present positive spatial autocorrelations, indicating an aggregation pattern of spatial relation. The second and fourth quadrants have negative spatial autocorrelations, indicating spatial heterogeneities. Figures 6(a)–(h) show that the scatter points are mainly distributed in the first and third quadrants, which indicates the existence of strong spatial positive correlations in Southern Jiangsu. Generally, *Global Moran's I* in each period is greater than 0.8 (Figs. 6(a)–(h)), which implies a conspicuously high degree of spatial autocorrelation in urban areas. In other words, at the township level, high density urban areas are adjacent to high density ones, while low density urban areas are adjacent to low density ones, which mean that the distribution of urban areas displays a prominent spatial aggregation pattern.

The fitting degree of the scatter diagram is *Global Moran's I* (i.e., the slopes of the straight lines in Figs. 6(a)–(h)). Fig. 6(i) shows the *Global Moran's I* of the distribution densities of urban areas based on the 274 townships from 1983 to 2007. We can find out that *Global Moran's I* rose from 1983 to 1995 forming a peak at point 1995, indicating the spatial aggregation phenomena of urban sprawl. Thereafter, *Global Moran's I* decreased gradually, indicating that the degree of spatial aggregation decreased, while spatial heterogeneities strengthened.

Overall, the sprawl in each period presents an aggregation pattern to a certain extent, as is reflected by the *Global Moran's I* of the distribution density of urban areas based on the 274 townships, respectively. The evolution of urban sprawl distribution pattern presents an obvious spatial agglomeration pattern. From 1983 to 1955, the prominent sprawl occurred around several townships, while from 1995 to 2007; the urban sprawl occurred in yet a wider range of townships, with a tendency to merge together forming a concentrated area and showed a spatial-homogeneity trend.

The LISA indices of each township were also used to reflect the spatial heterogeneities in urban areas. Figure 5 shows that in terms of spatial relation types, most cluster patterns were H-H and L-L relations, with few L-H

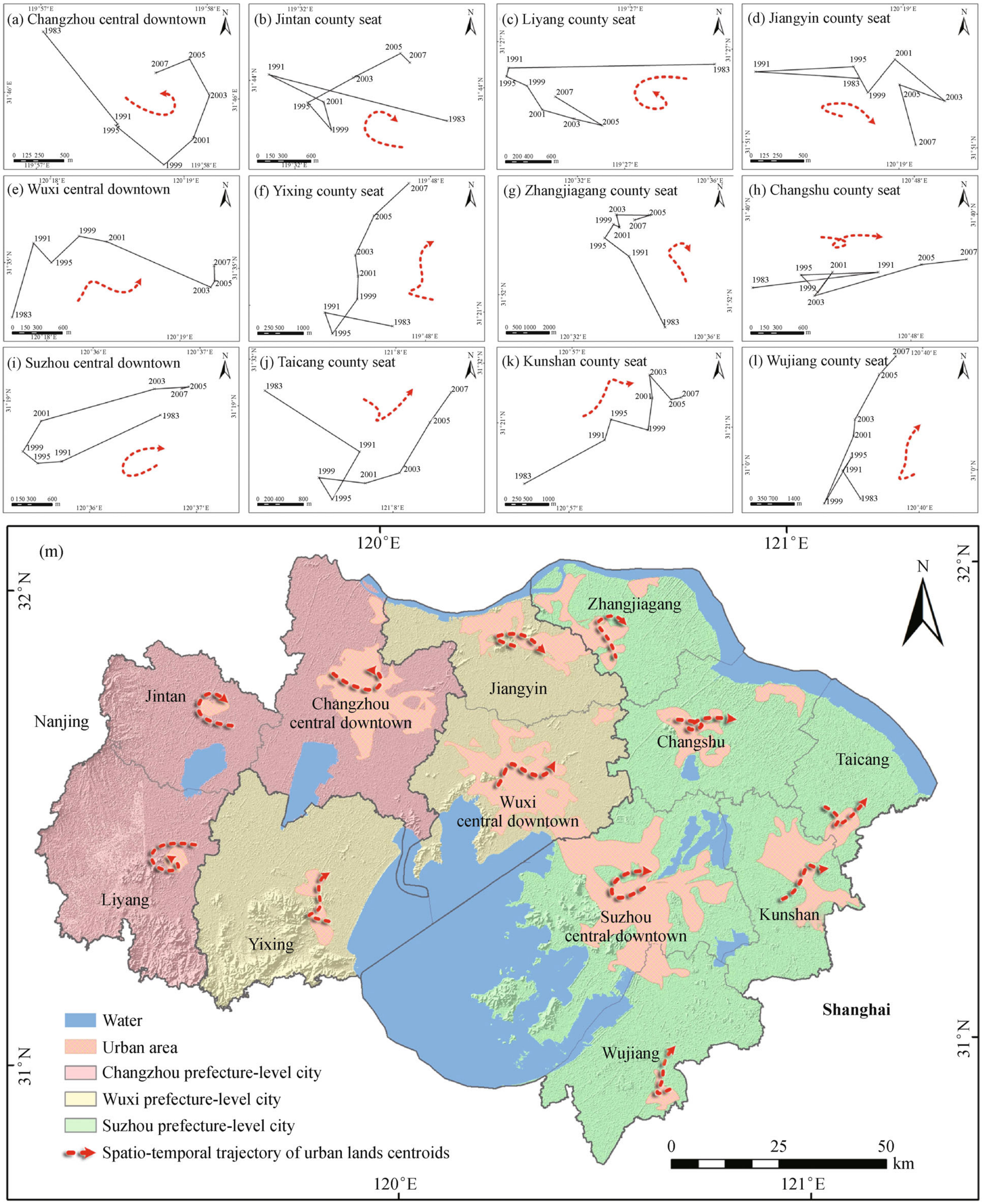

Fig. 5 Spatiotemporal trajectory of the centroids of urban areas in the three central downtowns and nine county seats in Southern Jiangsu.

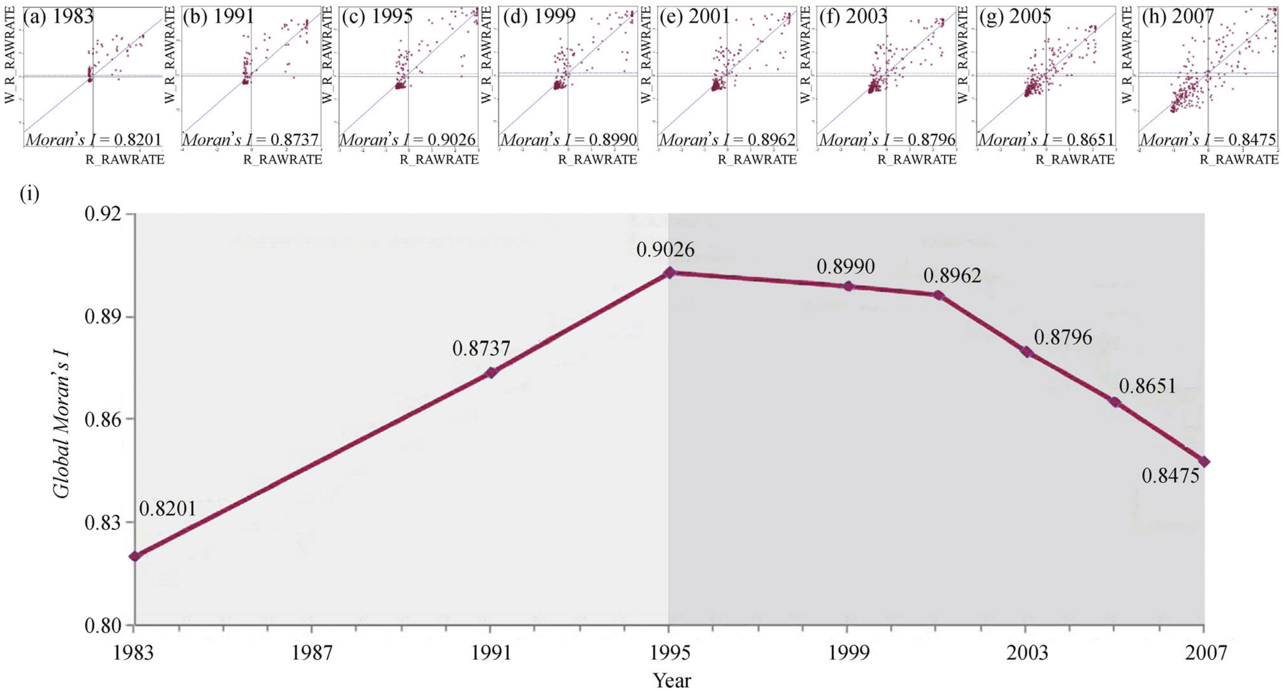

Fig. 6 *Global Moran's I* for the density of urban areas in Southern Jiangsu at the township level from 1983 to 2007; (a)–(h): scatter maps of *Moran's I* and (i) *Global Moran's I* change from 1983 to 2007.

relations and nearly no H-L relations. In terms of the quantities of these spatial relation types, the number of H-H relations grew from 24 townships in 1983 to 57 in 2007. L-L relations also increased until 2005, peaking at 63 in 2005 and then decreasing to 61 in 2007. By contrast, there were only three or four L-H relations on average. Finally, in terms of the spatial distribution of relations, H-H relations were mainly distributed in the central downtown areas of Suzhou, Wuxi, and Changzhou, where urban area densities were incredibly higher than the average for Southern Jiangsu. These areas constituted the growth drivers of urban sprawl showing a gradual increase (Figs. 7 (a)–(h)). The development of urban districts and their surroundings tended to be consistent, which constituted the "hot spots" of urban land, showing that their radiation capacities continued to grow. By contrast, L-L relations ("cold areas") tended to converge to the west of Southern Jiangsu, while L-H relations, including Xishan Town and several other towns, tended to increase, and were regarded as "depression zones" for regional economic development, due to the low distribution densities in these areas, yet higher in surrounding areas. In Figs. 7(g)–(h), Yushan Town was the only town regarded as an H-L relation after 2005; its distribution density was high, but that of the surrounding area was low.

Since 1983, two convergent groups have gradually formed in Southern Jiangsu: the low density urban zone in the western hilly region (green circle in Fig. 7) and the high density urban zone encompassing the three central downtown areas. During the initial stage when urban sprawl was self-governed and did not strongly influence other areas, the spread to surrounding townships was gradual and dispersment was continuous (red circles in Fig. 7). The formation of the earlier group may be attributed to the prevailing terrain, namely the hilly regions in the west and Tai Lake (Xishan Town, blue circle in Fig. 7). The latter reflects the notion that central downtown areas are always considered to be development drivers in a given urban system.

Nevertheless, the construction of industrial parks can affect urban sprawl patterns. For instance, no growth driver existed in Suzhou before 1995 (H-H type, Figs. 5(a) and 5(b)). However, the industrial park has been the growth driver of Suzhou ever since the China-Singapore Suzhou Industrial Park project was completed in 1994 (Fig. 5(c)). Similarly, a series of nationwide high-tech development parks have been established around these three central downtown areas, which may have contributed to high-density divergent zones in urban areas (red circles in Fig. 5).

5 Discussion

Urban sprawl is the consequence of various types of interaction between socioeconomic factors. In Southern Jiangsu, the urban sprawl manifests a multi-stage, diverse and complex spatio-temporal process.

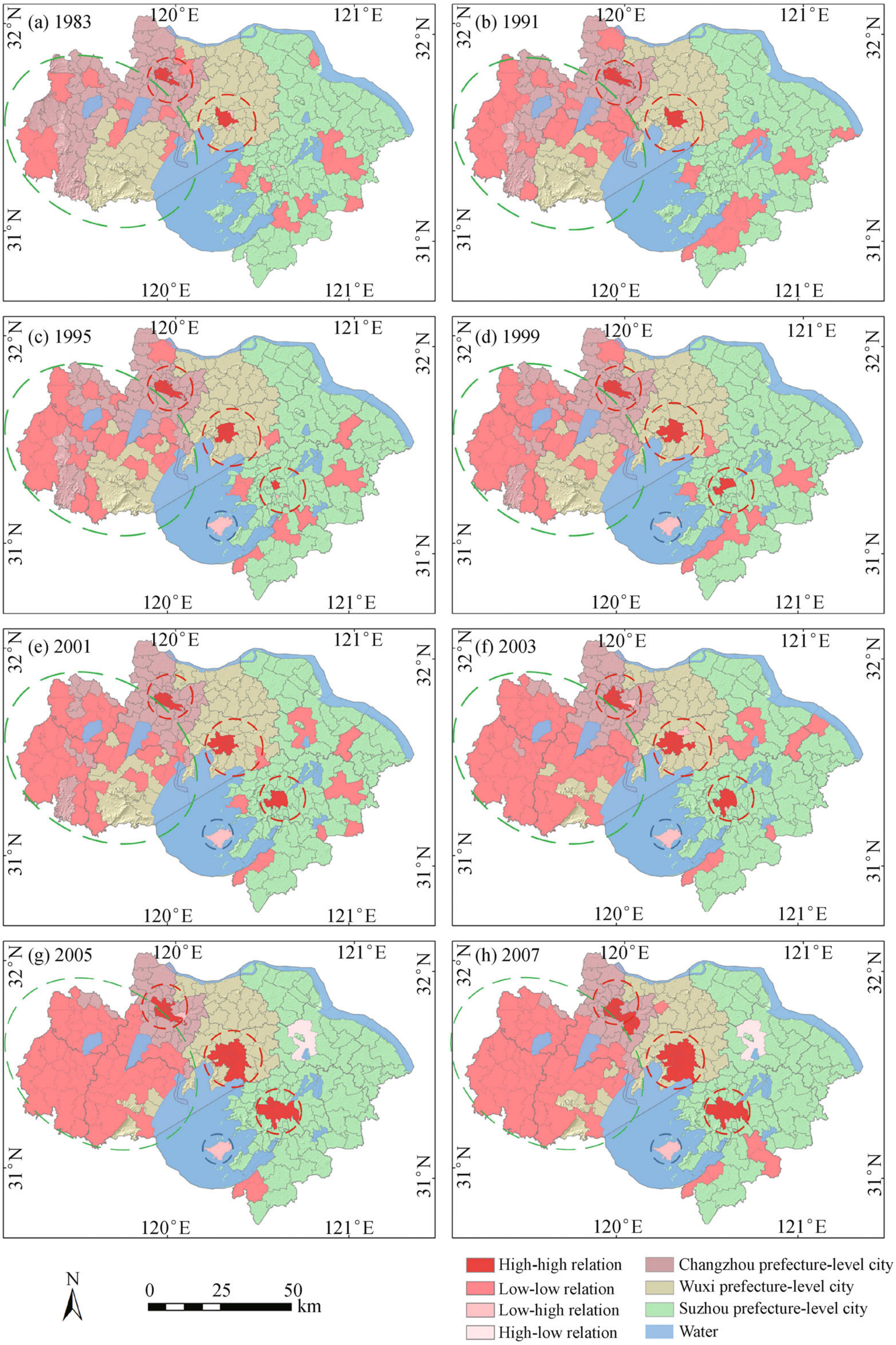

Fig. 7 Distribution of significant *Local Moran's I* for the density of urban areas in Southern Jiangsu at the township level from 1983 to 2007.

5.1 Mechanism among economic growth, urban population growth, and urban sprawl

Economic growth is the motivation of urban sprawl, urban land expansion, and also economic development promotion. China's economic development is rapid, but extensive, in need of many and varied types of land as its support and incentive, as reflected in the rapid expansion of urban areas. The relationship between GDP and the urban areas of the three prefecture-level cities for the eight samples were calculated. We found a highly positive linear correlation (R^2= 0.9848, samples = 24, Fig. 8(a)), which shows that investments in land area makes a significant contribution to Southern Jiangsu's economic growth. Similar to the urbanization process in the Pearl River Delta (Sit and Yang, 1997), Southern Jiangsu presents a typical "exo-urbanization" pattern.

The correlation analysis of the urban population and urban sprawl of the three prefecture-level cities also showed a positive linear correlation (R^2= 0.7689, samples = 24, Fig. 8(c)), albeit lower than that between GDP and the urban areas. This difference may be rooted in the definition of the "urban population." According to annual statistical yearbooks, the "urban population" actually represents the registered urban population, and thus it does not include floating populations. Drastic surges in floating populations have fostered rapid urbanization since 2000. Although such populations are not officially registered as permanent residents, they reside in urban areas and carry out non-agricultural activities. On this basis, they are undoubtedly part of the urban population. For instance, the floating population in Suzhou reached 5.39 million in 2010 compared with a registered population of 6.38 million. These numbers increased to 6.24 million and 6.39 million in 2011, respectively, making Suzhou the second largest immigrant city in China after Shenzhen.

We calculated the relationship between the total urban population (i.e., the sum of the registered urban population and the floating population) and the urban areas of the three prefecture-level cities for the eight samples (floating population data on Suzhou in 1991, Wuxi in 1991, and Changzhou in 1983 and 1991 are missing, hence 20 samples in total). Figure 8(c) illustrates the highly positive linear correlation for this relation (R^2= 0.9769, samples = 20). Assuming that the per capita possession of urban area is certain, population growth will inevitably lead to an increased demand for urban land.

Figures 8(a) and 8(c) show that the mechanism between urban areas, GDP, and the urban population among the three prefecture-level cities, demonstrate a similar trend, suggesting that the mechanism of urbanization in Suzhou, Wuxi, and Changzhou may be similar: the faster the economic development, the greater the appeal to the floating population, and the more rapid the urbanization process. Moreover, it is reasonable to infer from these figures that the current situation in Suzhou suggests the future path for Wuxi and Changzhou.

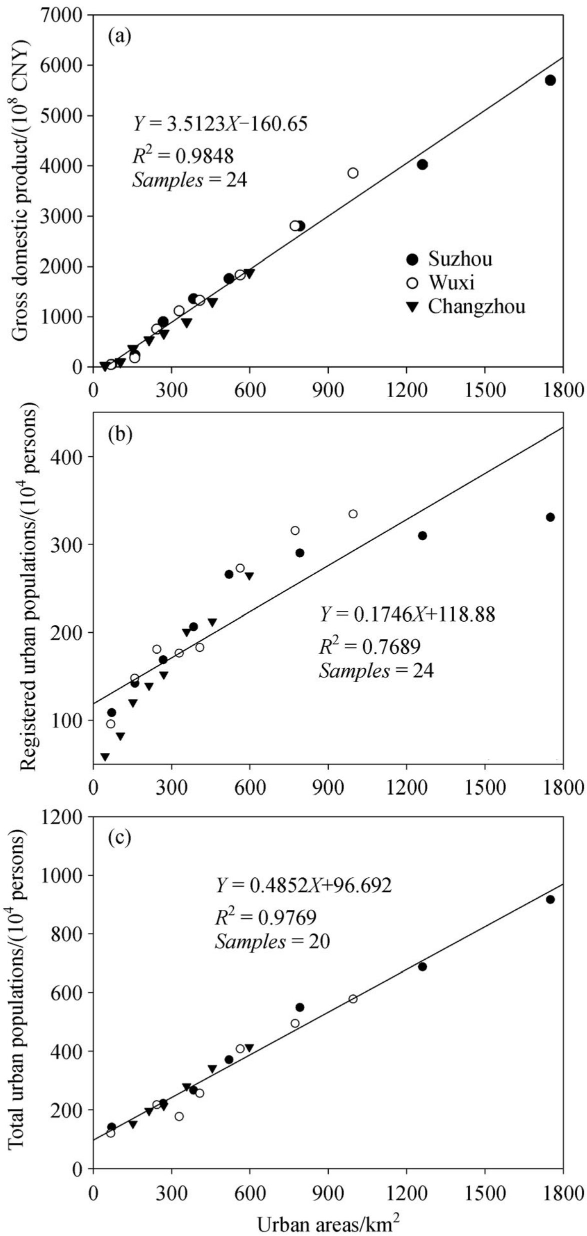

Fig. 8 Relation between GDP, registered urban populations, total urban populations, and urban areas: (a) GDP and urban area time series scatter plot of the three prefecture-level cities from 1983 to 2007; (b) registered urban populations and urban areas from 1983 to 2007; and (c) total urban populations and urban areas from 1983 to 2007.

5.2 Mechanism between China's Reform Policy and regional urban sprawl

Over the past 35 years, China has undergone significant stages of progression, each of which promote economic and social development with beneficial policies, in conjunction with a significant increase in urban sprawl. We can see that national policies and economic globalization influence the rate of urban sprawl. The reform and opening up policy has taken China into a stage of rapid urbanization (Lin, 1999). Many subsequent policies, especially that which established economic development zones in the Yangtze River Delta in 1985, caused rapid urbanization in Southern Jiangsu from 1983 to 1995 (Figs. 3(b)-(1)) making Southern Jiangsu one of the most developed regions in China.

However, this rapid and extensive development in China caused a number of issues, such as the depletion of resources and environmental pollution (Chen, 2007). Among these issues, extensive land use was the most serious. Arable land areas decreased by approximately 6.84×10^6 ha from 1986 to 1995 (Tan et al., 2005), which resulted in stricter arable land oversight policies and the implementation of the Basic Farmland Protection Regulation (in 1999, New Land Administration Law) issued from 1997 to 1999 (Lichtenberg and Ding, 2008). Affected by these policies and the Asian financial crisis (1997–1998), the urban sprawl rate slumped during 1999 (Fig. 3(b)-(2)).

After 2000, an incentive-based policy for the development of the Yangtze River, put forward by the Jiangsu Province government and China's accession to the World Trade Organization, led to a new round of rapid urban sprawl (Figs. 2(f)–(h), Fig. 3(b)-(3)). The turning point corresponds to the so-called Tieben event in Changzhou in 2004, caused by the Jiangsu Tieben Iron and Steel Co. by illegal appropriation of 4 km^2 arable land for a large-scale iron and steel-making project without government approval. As a result, Changzhou's urban expansion rate was slower than those of Suzhou and Wuxi from 2003 to 2005. Soon after this event, a policy that encouraged land utilization for participation in the country's macroeconomic regulation and control was issued, which resulted in another period of slow growth from 2005 to 2007. However, the expansion of urban areas in Changzhou grew again from 2005 to 2007 (Fig. 3(b)-(4)).

In general, national policies, such as industrial, population, land-use, housing, and regional development policies, have greatly influenced the urban sprawl process. Under such policies and the subsequent implementation of regulations, the urban sprawl rates of the three investigated prefecture-level cities in Southern Jiangsu all experienced peaks and troughs from 1983 to 2007. These policies also function to ease and balance the tendency of polarization between the high utilization ratio of central urban districts and the low utilization ratio of peripheral urban areas, which is reflected in the fact that the spatial homogeneity of urban land densities has decreased, and the tendency of spatial aggregation is eased. However, the interests of local governments do not always coincide with those of the central government, and the effect of national regulations depends on how rigorously these policies are implemented at the local level. On this basis, urban sprawl in Southern Jiangsu has not undergone continuous growth, but rather, a temporary suppression and a quicker rebound in the rates of urban sprawl.

6 Conclusions

Based on eight rounds of satellite images from 1983 to 2007, we applied spatial analysis and spatial autocorrelation analysis methods for the typical urban agglomeration of Southern Jiangsu, demonstrating the spatiotemporal dynamics of urban sprawl at three levels. The three major conclusions of the research are as follows:

1) On the whole, Southern Jiangsu has experienced rapid urbanization since 1983, with its urban areas growing more than 18-fold from 182.51 km^2 to 3,343.83 km^2 during the investigated period of 1983 to 2007. At the prefecture level, this degree of urban sprawl has presented significantly divergent growth patterns, with more than half of this vast growth occurring in the Suzhou prefecture-level city.

2) At the county level, clear spatial differentiations exist in the direction of the urban sprawl. In general, the centroids of all county seats in the Suzhou and Wuxi prefecture-level cities have an eastward tendency, while those of the county seats in the Changzhou prefecture tend westward.

3) At the township level, two convergent groups in Southern Jiangsu have gradually formed over time; namely, the low density urban zone in the western hilly region and high density urban zone surrounding the three central downtown areas. The urban areas adjacent to urban cores tend to merge together, showing a high-density convergent growth pattern, as do the western and southwestern townships in Southern Jiangsu, showing a low-density convergent growth pattern.

In the critical period of industrialization and urbanization in China, study on spatiotemporal dynamics of urban sprawl has important strategic significance to optimize the urban system and regional spatial structure. It would be beneficial to discover the general rules and development mode, and to also provide a theoretical basis for the development of China's urban agglomeration. Southern Jiangsu has undergone rapid urbanization over the past 30 years. While such rapid urban sprawl has promoted dramatic economic development and improved people's lives and well-being, it has also resulted in many environmental and ecological problems, which demand further examination. For example, studies of how to balance rapid urbanization with the conservation of the ecosystem could contribute to the literature in this regard.

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