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Spatiotemporal measurement of urbanization levels based on multiscale units:

A case study of the Bohai Rim Region in China

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Abstract: Urbanization is a complex process reflecting the growth, formation and development of cities and their systems. Measuring regional urbanization levels within a long time series may ensure healthy and harmonious urban development. Based on DMSP/OLS nighttime light data, a human–computer interactive boundary correction method was used to obtain information about built-up urban areas in the Bohai Rim region from 1992 to 2012. Consequently, a method was proposed and applied to measure urbanization levels using four measurement scale units: administrative division, land-sea location, terrain feature, and geomorphological types. Our conclusions are: 1) The extraction results based on DMSP/OLS nighttime light data showed substantial agreement with those obtained using Landsat TM/ETM+ data on spatial patterns. The overall accuracy was 97.70% on average, with an average Kappa of 0.79, indicating that the results extracted from DMSP/OLS nighttime light data were reliable and could well reflect the actual status of built-up urban areas. 2) Bohai Rim's urbanization level has increased significantly, demonstrating a high annual growth rate from 1998 to 2006. Areas with high urbanization levels have relocated evidently from capital to coastal cities. 3) The distribution of built-up urban areas showed a certain degree of zonal variation. The urbanization level was negatively correlated with relief amplitude and altitude. A high level of urbanization was found in low altitude platforms and low altitude plains, with a gradual narrowing of the gap between these two geomorphological types. 4) The measurement method presented in this study is fast, convenient, and incorporates multiple perspectives. It would offer various directions for urban construction and provide reference values for measuring national-level urbanization.

Keywords: nighttime light data; urbanization level; multiscale units; Bohai Rim

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1 Introduction

Urbanization is the most intuitive reflection of the urban development process (Lv *et al*., 2008). Accelerated urbanization in recent years has resulted in land expansion outpacing population growth (Yao *et al*., 2012), leading to serious problems such as overly rapid and uncontrolled urban spatial development (Yao *et al*., 2011; Lu *et al*., 2007). Consequently, obtaining information on urbanization and measuring regional urbanization levels in a quick and efficient way will ensure the adjustment and optimization of regional urbanization patterns, and have both practical value and research significance.

Currently, data sources of China's urbanization used in scientific research are primarily statistical yearbooks (Guo *et al*., 2014; Fan *et al*., 2014; Chen *et al*., 2010; Ou *et al*., 2008; Ou *et al*., 2012; Zhu *et al*., 2014), and urban land use information extracted from remote sensing images (Li *et al*., 2007; Chen *et al*., 2015). Study areas include individual cities (Chen *et al*., 2015), urban agglomerations (Guo *et al*., 2014; Li *et al*., 2007; He *et al*., 2015), provinces (autonomous regions) (Fan *et al*., 2014; Ou *et al*., 2008; Ou *et al*., 2012), and even the nation as a whole (Chen *et al*., 2010; Zhu *et al*., 2014; Chen *et al*., 2003). Because of limited accessibility of large-scale remote sensing images and the high cost of extracting urban land use information, studies entailing the measurement of long-term regional urbanization are mainly conducted based on statistical data, resulting in a lack of spatial information. Besides, the measurement units are dominated by administrative boundaries, and are lack of natural, cultural and other types of factors, making it difficult to fully capture spatio-temporal variations at long-term regional urbanization levels.

The Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) can detect city lights and other low intensity signals emanating from small-scale residential areas, traffic, and fishing vessels at night, thereby enabling urban areas to be distinguished from rural areas (Elvidge *et al*., 2007). This type of sensor is suitable for conducting dynamic surveys of the urbanization process, because its time and spatial resolution are similar to those of the National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) (Chen *et al*., 2003). Easy accessibility and timeliness have resulted in the wide-scale use of nighttime light data for extracting urban land use information (He *et al*., 2006; Cao *et al*., 2009; Shi *et al*., 2014; Su *et al*., 2015), population simulations (Lo, 2001, 2002; Zhuo *et al*., 2005; Doll and Pachauri, 2006), economic estimations (Doll *et al*., 2006; Ghosh *et al*., 2010; Henderson *et al*., 2012; Li *et al*., 2013; Elvidge *et al*., 2009), hazard evaluations (Cahoon *et al*., 1992; Tuttle, 2007), energy consumption assessments (Amaral *et al*., 2005; Chand *et al*., 2009; Kiran *et al*., 2009; He *et al*., 2012), and identification of environmental problems (Imhoff *et al*., 2000, 2004). However, measurement of urbanization levels using nighttime light data is relatively rare in current studies. This has caused a lack of strong data support for making decisions and recommendations on regional urban development.

The Bohai Rim region is an important area of economic growth in northern China, and is also an optimal development zone at national level in relation to the main function zoning. In recent years, rapid urbanization of the Bohai Rim has brought in its wake a series of ecological and environmental problems. Developing a comprehensive understanding of spatial patterns of the Bohai Rim's urbanization will enable strategic decisions to be made regarding its urban development. This requires measurement and corresponding analysis of the Bohai Rim's urbanization level based on a scientific and effective measurement method.

Considering 44 cities in the Bohai Rim as objects of our study, we acquired possible threshold intervals of different cities for the year 1992, 1998, 2006, and 2012 using the statistical comparison method. We then applied the best threshold value using the human–computer interactive boundary correction method. We subsequently obtained information regarding built-up urban areas in the study years. Next, we used high spatial resolution Landsat EM/ETM+ data to evaluate the reliability of the extraction results based on DMSP/OLS nighttime light data. This evaluation confirmed that the extracted urban land well reflected the actual status of urban development in the corresponding periods. Accordingly, we developed a method for measuring the urbanization level of the Bohai Rim from 1992 to 2012 using DMSP/OLS nighttime light data and four different measurement scale units including administrative division, land-sea location, terrain feature, and geomorphological types. Unlike previous studies that used measurement units based solely on administrative divisions, we also considered other factors such as land-sea locations, terrain features, and geomorphological types to develop a comprehensive understanding of the urbanization status in the Bohai Rim region. This can facilitate the formulation of policies to promote a sustainable urbanization process. This study filled a research gap on spatiotemporal measurements of regional long-term urbanization levels. It also enabled a rapid measurement of urbanization levels at different scales. Compared to previous similar studies, the method presented in this paper has a stronger application and popularization value.

2 Data sources and preparation

2.1 Study area

The Bohai Rim region is located within 33°30′N–46°30′N and 104°35′E–125°40′E and covers an area of 52.2×10^4 km^2. Viewed as China's "third engine," it encompasses a total of 44 cities, including Beijing and Tianjin Municipalities, and Hebei, Shandong, and Liaoning provinces (Figure 1). The study area is located between mid-temperate and warm-temperate zones, where most of the area is situated in the warm-temperate zone with a semi-humid climate. Landforms and terrains of the Bohai Rim are very complex, including Shandong Hills, Haihe River Plain, Bashang Plateau, Liaohe River Plain, and Eastern Liaoning Hills. Main rivers in the region are the Yellow, Haihe, Liaohe, and Luanhe rivers. Three main railway networks, namely, the Beijing–Guangzhou, Beijing–Kowloon, and Beijing–Shanghai, link Bohai Rim to eastern, south-central, and southern China, respectively, making it a key hub in China's transportation network.

2.2 Data description

2.2.1 Statistical data

The values for built-up urban areas were obtained from statistical yearbooks of Chinese cities (National Bureau of Statistics, 1995, 2000, 2008, 2013). We collected information on the built-up urban areas of 44 cities in the Bohai Rim for the years 1993, 1998, 2007, and 2013. These data sources are the main references when we extract built-up urban areas from

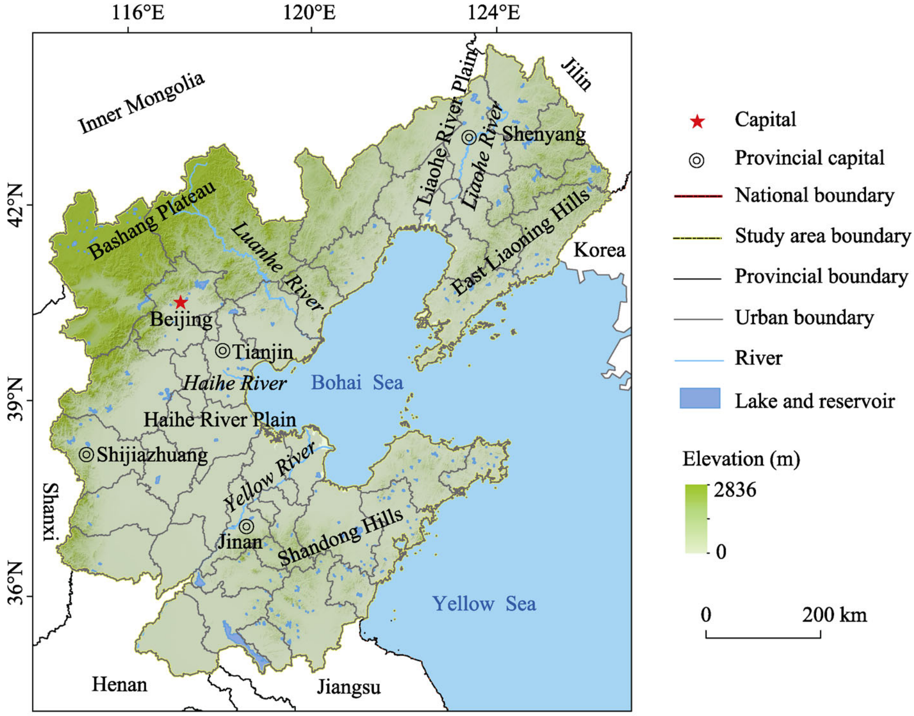

Figure 1 An overview of the Bohai Rim region

DMSP/OLS nighttime light data in this study.

2.2.2 Geomorphological data

Geomorphological data were derived from 1:1,000,000 digital geomorphological database of China. Seven layers were classified based on combinations of landforms' morphological characteristics and their genesis. These layers are: basic morphology and altitude, genesis, sub-genesis, morphology, micro-morphology, slope and aspect, and material and lithology (Cheng *et al*., 2011). The digital geomorphological database was created based on visual interpretation of Landsat TM/ETM images, SRTM-DEM, and maps of historical geomorphology (Cheng *et al*., 2011). In this study, we selected the first layer (Zhou *et al*., 2009) as the geomorphological unit, and extracted the basic morphological types of the Bohai Rim region (Table 1) by spatial overlay analysis.

2.2.3 DMSP/OLS nighttime light data

DMSP/OLS nighttime light data were obtained from the State Key Laboratory of Resources and Environmental Information System (SKLREIS). The time series data for DMSP/OLS stable nighttime light imagery spanning the years 1992–2012 were initially procured from NOAA's National Geophysical Data Center and subsequently rectified by applying a second order regression model (Elvidge *et al*., 2009) to eliminate inter-annual variations and response differences among sensors. The spatial resolution was 30 arc-seconds (approximately 1 km at the equator and 0.8 km at 40°N) (Ma *et al*., 2012). We extracted DMSP/OLS nighttime light data for 1992, 1998, 2006, and 2012 for 44 cities in the Bohai Rim (Figure 2) by setting the mask using administrative boundary data.

Table 1 Basic geomorphological types in the Bohai Rim

Altitude	Low altitude	Middle altitude
Relief	(< 1000 m)	(1000–3500 m)
Plain (< 30 m)	Low altitude plain (LAP)	Middle altitude plain (MAP)
Platform (> 30 m)	Low altitude platform (LAPF)	Middle altitude platform (MAPF)
Hill (< 200 m)	Low altitude hill (LAH)	Middle altitude hill (MAH)
Low relief mountain (200–500 m)	Low relief low altitude mountain (LRLAM)	Low relief middle altitude mountain (LRMAM)
Middle relief mountain (500–1000 m)	Middle relief low altitude mountain (MRLAM)	Middle relief middle altitude mountain (MRMAM)
High relief mountain (1000–2500 m)	—	High relief middle altitude mountain (HRMAM)
Highest relief mountain (> 2500 m)	—	—

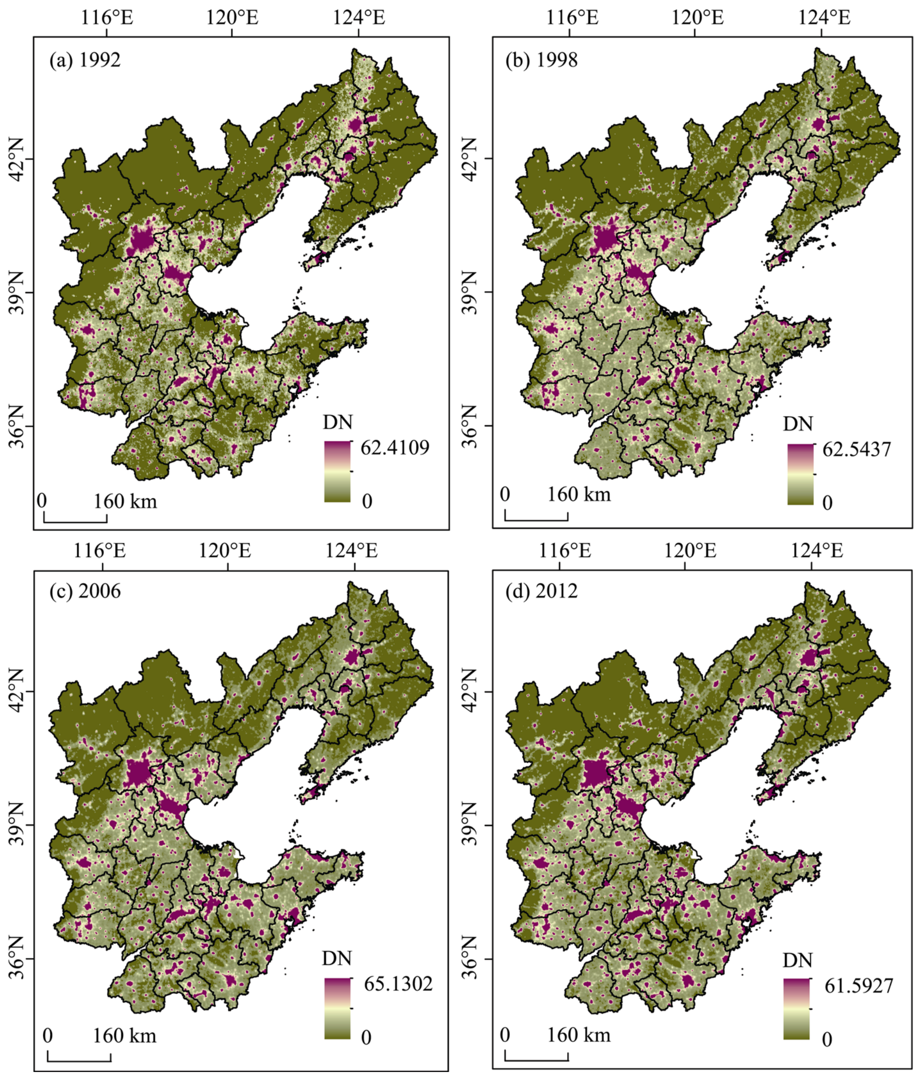

Figure 2 DMSP/OLS images of the Bohai Rim region from 1992 to 2012

2.3 Multiscale measurement units

2.3.1 Measurement units for administrative divisions

Measurement units for administrative divisions were delineated with three different types of measurement units. The first measurement unit was a regional unit comprising the entire region of the Bohai Rim. The second measurement unit was a city comprising the 44 municipal administrative units in the region, each of which constituted a measurement unit. The third measurement unit was an urban agglomeration unit. There were three such units in the Bohai Rim: Beijing–Tianjin–Hebei, East Liaoning Peninsula, and Shandong Peninsula. Each of these urban agglomerations was regarded as a measurement unit (Figure 3).

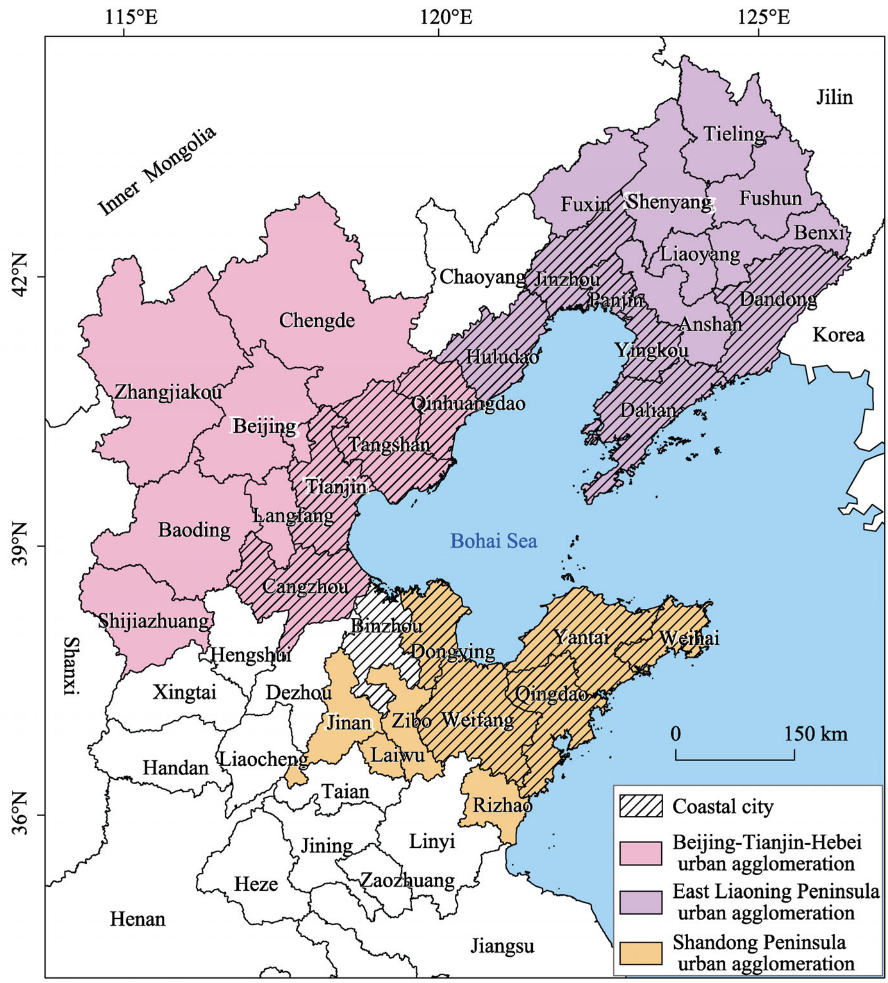

Figure 3 Urban agglomerations and coastal cities in the Bohai Rim

2.3.2 Measurement units based on land-sea location

Two types of measurement units based on land-sea locations were delineated. The first was comprised of coastal and non-coastal city units. A total of 17 coastal cities were included: Dalian, Dandong, Yingkou, Panjin, Jinzhou, Huludao, Qinhuangdao, Tangshan, Tianjin, Cangzhou, Binzhou, Dongying, Weifang, Yantai, Weihai, Rizhao, and Qingdao. Coastal and non-coastal cities were two main districts, with each of them constituting a measurement unit (Figure 3). The second measurement unit was distance from the coastline. The Bohai Rim region was subdivided into two types of districts located within and beyond 200 km of the coastline, respectively, with each district constituting a unit of measurement.

2.3.3 Measurement units based on terrain features

Two types of measurement units based on terrain features were considered. The first type was relief units. Five relief amplitudes were selected for the Bohai Rim region. These were: <30 m, 30–200 m, 200–500 m, 500–1000 m, and >1000 m. The second type consisted of altitude units. Five levels of altitude were observed for the Bohai Rim region: <50 m, 50–150 m, 150–300 m, 300–1000 m, and >1000 m.

2.3.4 Measurement units based on geomorphological types

The Bohai Rim region has 11 geomorphological types (Figure 4), with each type constituting a measurement unit.

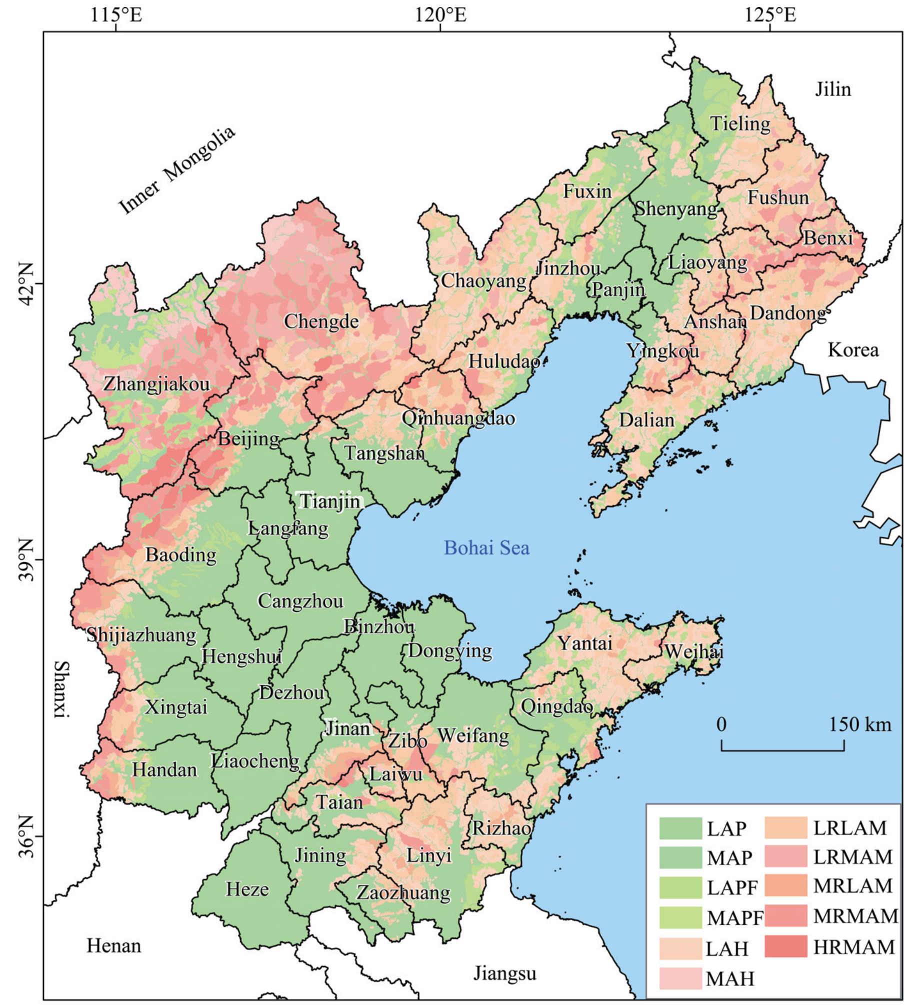

Figure 4 Geomorphological types in the Bohai Rim region

3 Methods for measuring urbanization levels

3.1 Extraction of built-up urban areas

Based on previous studies (e.g. He *et al*., 2006a), two basic assumptions were used to extract built-up urban areas in this study. The first assumption was that the statistical data published by the National Bureau of Statistics truly reflected built-up urban areas. Thus, the extraction results should be as close as possible to match the statistical data. The second assumption was that raster patches derived from the previous period of nighttime light data should be retained for use during the subsequent period.

Considering threshold diversity among the 44 cities in the Bohai Rim during different periods, we extracted their built-up urban areas for the years 1992, 1998, 2006, and 2012. Three steps were taken for extracting built-up areas as follows:

(1) Dynamic thresholds for cities' nighttime light data during each period were set using the dichotomy method (He *et al*., 2006b). Statistical values of built-up urban areas for each dynamic threshold were subsequently compiled. Results that deviated significantly from the statistical data were removed. Lastly, the possible threshold interval was determined.

(2) Boundaries of each built-up urban area under different thresholds were manually modified based on a combination of urban expansion directions and the two previously described basic assumptions. Unreasonable thresholds were excluded and the best threshold of built-up urban areas for each period was determined.

(3) Boundaries for the best thresholds during different periods were manually modified according to the two basic assumptions and referring to the urban expansion directions.

By comparing with the statistical data, we evolved a method to conduct human–computer interactive boundary correction. Consequently, we derived the built-up urban area of the Bohai Rim in 1992, 1998, 2006, and 2012 (Figure 5), with relative error less than ±4% between the extraction results and the statistical data (Table 2).

3.2 Accuracy assessment of the extraction results

The high resolution Landsat TM/ETM+ data were used to verify the accuracy and reliability of urban land extraction results. Given that the spatial resolution of the Landsat TM/ETM+ was 30 m, which was well above the 1 km spatial resolution of the DMSP/OLS nighttime light data, we assume that the use of Landsat TM/ETM+ data to evaluate the accuracy of the urban land information derived from the DMSP/OLS nighttime light data was feasible and reliable (Yang *et al*., 2013; Henderson *et al*., 2003). Considering data collection and cost factors, we selected Beijing as a representative example for calculating the overall accuracy (OA) and the Kappa index for the evaluation of accuracy (Nishii *et al*., 1999).

3.3 Construction of indexes on urbanization levels

The level of urbanization can be evaluated using the ratio between urban land and total land (Pan *et al*., 2014). Accordingly, after deriving the built-up urban area from nighttime light data, we constructed an index to measure levels of urbanization in the Bohai Rim from 1992 to 2012. This urbanization level index, U, was calculated as:

$$U = \frac{C}{L} \times 100\% \tag{1}$$

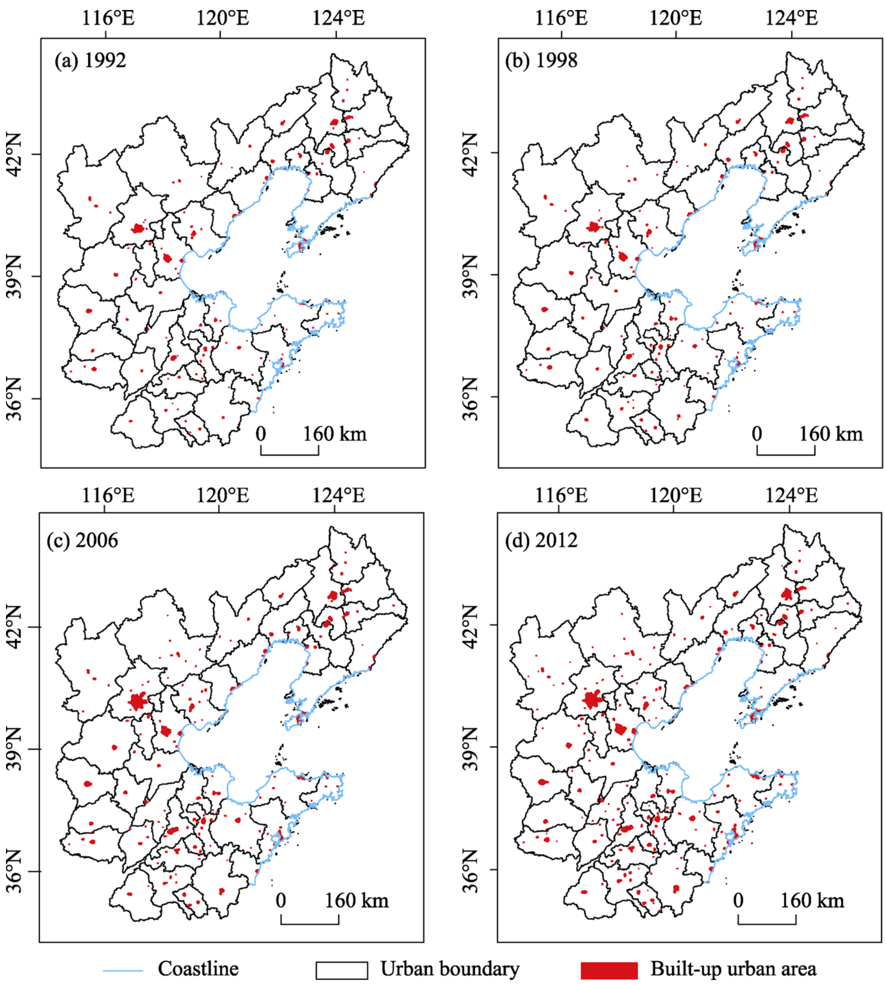

Figure 5 Built-up urban areas of the Bohai Rim derived from DMSP/OLS data for the years 1992, 1998, 2006, and 2012

where C is the region's built-up urban area (km^2) and L is the region's total land area (km^2).

To analyze long-term variations of the urbanization level, we introduced the average annual urbanization growth rate, V, calculated as:

$$V = \left(\sqrt[t_b - t_a]{U_{t_b} / U_{t_a}} - 1 \right) \times 100\% \tag{2}$$

where U_{t_b} and U_{t_a} are urbanization levels for the year t_b and t_a, respectively. The time interval during the measurement period was expressed by t_b–t_a.

4 Analysis of urbanization measurement levels

Considering data collection and cost factors, we selected Beijing as a representative example to verify the accuracy of our extraction of urban land, and to evaluate the reliability of our results. Our assessment showed that the results extracted using DMSP/OLS nighttime light

Table 2 Relative errors between the extraction results and the statistical data

City	Relative error (%)				City	Relative error (%)			
	1992	1998	2006	2012		1992	1998	2006	2012
Beijing	–1.88	3.03	–1.53	3.91	Liaoning	–0.68	2.95	0.29	–0.81
Tianjin	–1.91	2.67	2.41	3.18	Panjin	–2.88	3.29	–1.11	1.71
Shijiazhuang	–1.41	–0.12	–0.15	–0.02	Tieling	–1.09	2.81	–3.82	3.77
Tangshan	–1.18	0.00	–0.94	0.15	Chaoyang	2.37	0.82	–1.10	2.00
Qinhuangdao	0.65	–1.52	0.43	6.61	Huludao	1.57	–1.23	0.83	–0.81
Handan	–0.69	1.26	–0.70	1.12	Jinan	–0.60	–0.24	–0.09	0.00
Xingtai	0.38	0.18	0.17	0.82	Qingdao	–1.90	1.40	1.06	0.39
Baoding	1.24	0.44	–0.52	–0.20	Zibo	–0.42	0.33	0.14	–0.20
Zhangjiakou	–2.72	–1.42	1.27	2.29	Zaozhuang	1.58	0.66	1.58	1.29
Chengde	–0.77	2.83	–1.05	–0.05	Dongying	–1.42	–0.87	1.58	1.75
Cangzhou	–2.22	–2.46	0.30	1.40	Yantai	–0.02	0.13	0.15	–0.20
Langfang	–2.24	–0.07	–0.41	3.68	Weifang	–0.22	–0.87	0.46	0.32
Hengshui	–0.42	1.32	–0.19	3.65	Jining	0.83	–2.69	1.99	–0.34
Shenyang	–3.27	–0.17	–0.17	0.07	Taian	–1.84	1.74	–1.13	0.63
Dalian	–3.21	–0.79	–0.30	0.06	Weihai	0.49	–2.04	0.34	0.02
Anshan	–1.23	–1.02	–0.78	–0.18	Rizhao	1.58	0.17	1.40	1.77
Fushun	0.22	0.35	0.65	2.63	Laiwu	–2.90	–0.94	1.04	0.69
Benxi	–1.28	1.32	–0.32	2.07	Linyi	–0.94	1.74	–0.33	0.23
Dandong	–1.44	–1.23	–1.92	1.81	Dezhou	–1.10	–1.72	1.86	0.47
Jinzhou	–1.04	–2.00	2.18	2.07	Liaocheng	2.43	–0.42	–1.26	1.15
Yingkou	1.07	–0.25	–0.74	2.63	Binzhou	–0.94	–2.09	–1.01	–0.16
Fuxin	–1.24	0.59	2.42	1.22	Heze	0.17	–1.97	–0.60	1.36

data could well reflect the actual status of urban development. We used four different measurement scale units, namely, administrative division, land-sea location, terrain feature, and geomorphological types, to measure Bohai Rim's urbanization level and to analyze its spatiotemporal variation from 1992 to 2012. Overall, urban expansion was clearly evident for each measurement scale unit from 1998 to 2006. Gaps in urbanization levels, based on the different measurement scale units, were significant and showed an increasing trend.

4.1 Evaluation of accuracy

High resolution remote sensing images—namely, Landsat 4/5 TM data for Beijing, taken in June 1992, November 1998, and April 2006, and Landsat 7 ETM+ SLC-off data for Beijing, taken in May 2012—were obtained from the United States Geological Survey (http://glovis.usgs.gov/). After preprocessing reference data (e.g., destriping and geometric correction), we applied visual interpretation as our primary method and supervised classification as our supplementary method to extract information of built-up urban areas from Landsat TM/ETM+ data. Assuming that the above information accurately reflected the actual status of the built-up urban areas for the corresponding period, we compared this information with our extraction results based on DMSP/OLS nighttime light data. We subsequently calculated the overall accuracy and Kappa index of the extraction results based on DMSP/OLS nighttime light data for Beijing during the different study periods (Table 2 and Figure 6). The accuracy evaluation revealed that the average value of the overall accuracy

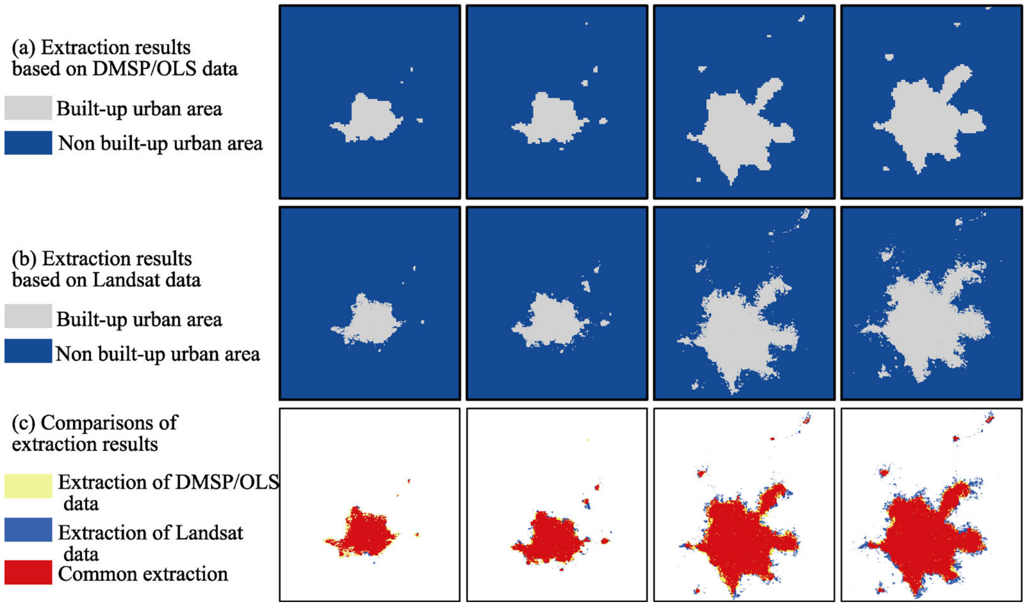

Figure 6 Accuracy assessment of selected urban areas in the Bohai Rim using Landsat TM/ETM+ data

Table 3 Accuracy assessment of selected urban areas in the Bohai Rim using Landsat TM/ETM+ data

	Landsat extraction results / DMSP/OLS extraction results	Urban (%)	Non-urban (%)	Total (%)
	Urban (%)	2.19	0.53	2.72
1992	Non-urban (%)	0.59	96.69	97.28
	Total (%)	2.78	97.22	100.00
		OA = 98.88%; Kappa = 0.79		
	Urban (%)	2.76	0.31	3.07
1998	Non-urban (%)	1.26	95.67	96.93
	Total (%)	4.02	95.98	100.00
		OA = 98.43%; Kappa = 0.77		
	Urban (%)	6.62	0.75	7.37
2006	Non-urban (%)	2.34	90.29	92.63
	Total (%)	8.96	91.04	100.00
		OA = 96.91%; Kappa = 0.79		
	Urban (%)	7.50	0.50	8.00
2012	Non-urban (%)	2.93	89.07	92.00
	Total (%)	10.43	89.57	100.00
		OA = 96.57%; Kappa = 0.80		

and the Kappa index were 97.70% and 0.79, respectively. The result obtained from DMSP/OLS nighttime light data showed substantial agreement with information based on Landsat TM/ETM+ data on spatial patterns. Therefore, the built-up urban area extracted from DMSP/OLS nighttime light data could be a good reflection of the actual status of urban development in the Bohai Rim region in 1992, 1998, 2006, and 2012.

4.2 Units based on administrative division

From 1992 to 2012, the total built-up area of the Bohai Rim region increased from 3104.58 km^2 to 8060.51 km^2, while the total urbanization level rose from 0.60% to 1.56%. The urbanization level rose annually with an average of 0.05%, and the average annual growth rate was 4.89%. Between 1992 and 1998, Bohai Rim's urbanization proceeded at a slow pace with an average annual growth rate of 3.16%. However, between 1998 and 2006, it showed a sharp increase with an average annual growth rate of 6.50%. The growth rate decreased slightly from 2006 to 2012 with an average annual growth rate of 4.50%. Variations in the urbanization level based on municipal administrative units are provided in Figure 7.

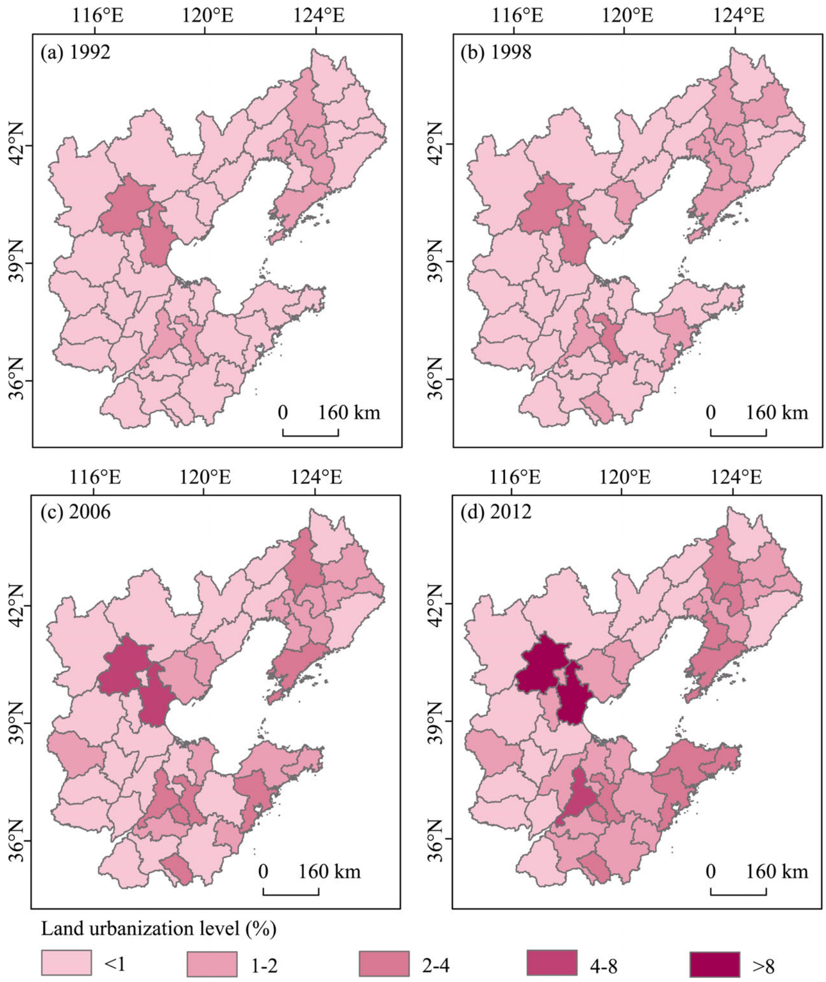

Figure 7 Urbanization levels of different cities in the Bohai Rim region from 1992 to 2012

Different cities showed varying degrees of evolution in their urbanization levels. Urbanization levels in Beijing and Tianjin have always been much higher than those of other cities. High value areas of urbanization were initially distributed in metropolitan locations concentrated in capitals. However, these have recently extended to coastal city areas, with Qingdao as the center, and ultimately giving rise to four nuclear types of urbanization patterns centering on Beijing, Shenyang, Jinan, Shijiazhuang, and Qingdao. The shift of high value areas has evidenced the spatial characteristic of being located close to the coast.

Based on the comparison of urbanization levels among urban agglomeration units, relevant characteristics of the three major urban agglomerations in the Bohai Rim region is shown in Figure 8a. The urbanization level of Beijing–Tianjin–Hebei urban agglomeration was always higher than that of the entire region. Between 1992 and 2002, urbanization level of the Shandong Peninsula urban agglomeration was below that of the Bohai Rim. However, urbanization gradually increased over time, and had surpassed the level of entire region after 2002. The disparity in the urbanization levels between Shandong Peninsula and the Bohai Rim as a whole showed a trend of first decreasing and then increasing. In the last two decades, urbanization level of the East Liaoning Peninsula urban agglomeration has shown a slight increase. During the first decade, the urbanization level of this area was higher than that of the whole region, and the gap between them was shrinking. However, during the latter decade, the gap increased again, and the urbanization level of this agglomeration dipped below that of the region. During the period from 1992 to 2012, the Shandong Peninsula urban agglomeration evidenced the highest average annual growth rate (7.25%), followed by the Beijing–Tianjin–Hebei urban agglomeration (4.55%). The East Liaoning Peninsula urban agglomeration had the lowest rate (3.14%). During the last two decades, the average annual growth rate in the East Liaoning Peninsula urban agglomeration maintained a steady rise, while those of the Beijing–Tianjin–Hebei and Shandong Peninsula urban agglomerations first increased and subsequently decreased.

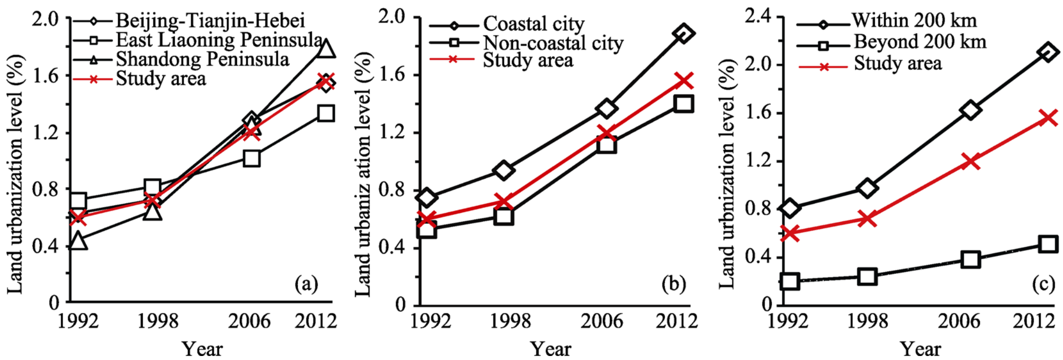

Figure 8 Urbanization levels of different regional units in the Bohai Rim

4.3 Units based on land-sea location

Figure 8b shows the characteristics of urbanization in coastal and non-coastal cities in the Bohai Rim region. The urbanization levels of coastal cities were always higher than those of the non-coastal cities and of the region as a whole. However, from 1992 to 2012, the average annual growth rate of urbanization in non-coastal cities (5%) was slightly higher than the rate in coastal cities (4.73%). Specifically, the average annual growth rate of the non-coastal cities (7.63%) was higher than that of coastal cities (4.81%) between 1998 and 2006. However, the rate was lower than that of coastal cities during the other two periods.

Figure 8c shows the characteristics of areas located at different distances from the coastline in the Bohai Rim. Levels of urbanization in areas within 200 km of the coastline were much higher than those located beyond 200 km. The average annual growth rate of urbanization in areas within 200 km of the coastline was slightly greater than that of areas beyond 200 km, and the rate of both areas showed a trend of first increasing and then decreasing.

4.4 Units based on terrain features

Our distribution analysis of the built-up urban areas in locations with different reliefs (Figures 9a and 10a) revealed that built-up urban areas were mainly distributed in locations where the relief was below 30 m. Locations where the relief ranged from 30 m to 200 m evidenced some built-up urban areas, while there were fewer such areas in locations where the relief was above 200 m. The urbanization growth trends in areas with varying relief units differed, with the growth trend being more apparent in locations where the relief was below 30 m. The level of urbanization was thus negatively correlated with relief amplitude. Promotion of urban development in locations where relief ranges from 30 m to 200 m could thus be of considerable value in helping to ensure sustainable development of the urbanization spatial pattern in the Bohai Rim.

Our distribution analysis of the built-up urban areas in locations at different altitudes (Figures 9b and 10b) revealed that more than 93.5% of the built-up urban areas were distributed in location at altitudes below 150 m, and especially in locations at altitudes below 50 m. Levels of urbanization in areas below 50 m were slightly higher than those of the areas at altitudes ranging between 50 m and 150 m, with this gap evidencing an increasing trend. Urbanization levels in areas above 150 m were evidently lower than those in low altitude areas. Thus, the level of urbanization was negatively correlated with altitude. In recent years, areas at altitudes below 50 m have undergone a phase of accelerated urbanization. Consequently, promotion of urban development in areas at altitudes ranging from 50 m to

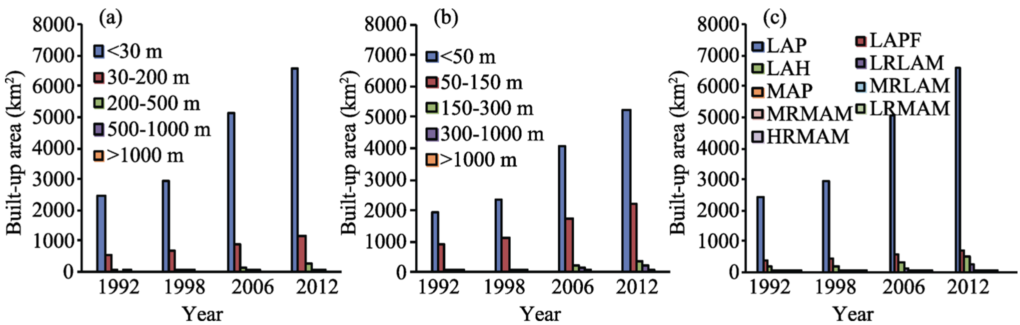

Figure 9 Built-up urban areas of different topographical units in the Bohai Rim from 1992 to 2012

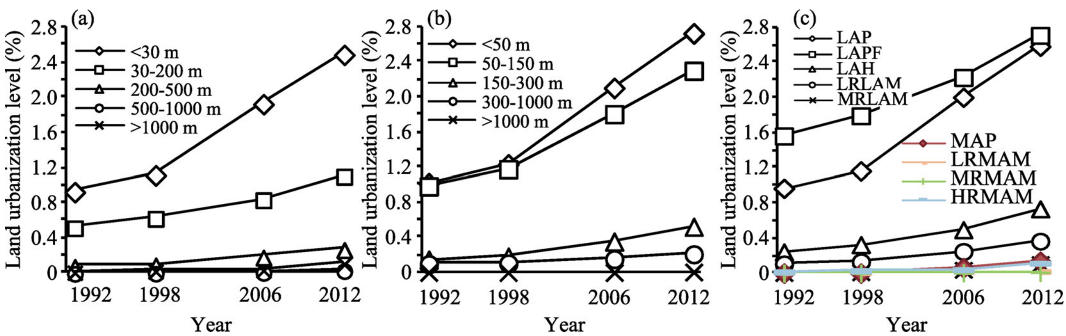

Figure 10 Urbanization levels of different topographical units in the Bohai Rim from 1992 to 2012

150 m could be an important direction for urban construction.

4.5 Units based on geomorphological types

Our analysis results revealed that the built-up urban areas were distributed in locations characterized by nine geomorphological types (Figures 9c and 10c). These included low altitude plains, low altitude platforms, low altitude hills, low relief and low altitude mountains, middle relief and low altitude mountains, middle altitude plains, low relief and middle altitude mountains, middle relief and middle altitude mountains, and high relief and middle altitude mountains. The majority of the built-up urban areas were located in low altitude plains, and some also found in low altitude platforms and hills. The level of urbanization in low altitude platforms was higher than that in locations characterized by other geomorphological types. However, the level of urbanization in low altitude plains rose faster, and the gap between these two geomorphological types shrunk evidently. Slowing down the pace of urbanization in low altitude platforms and stimulating the urbanization process in low altitude hilly areas could facilitate timely and proper control of this process in the Bohai Rim region.

5 Discussion

Comparing with the statistical data for the 44 cities in the Bohai Rim region, we determined optimal thresholds and obtained spatial information of the built-up area for each city for the years 1992, 1998, 2006 and 2012 by applying a human–computer interactive boundary correction method. Compared with the built-up urban areas extracted from Landsat TM/ETM+ data, the built-up urban area extracted from DMSP/OLS nighttime light data had an average overall accuracy of 97.70% and an average Kappa coefficient of 0.79. This indicated that the method has a high reliability and could well reflect the actual status of the built-up urban areas. Consequently, we developed a method for measuring urbanization levels using DMSP/OLS nighttime light data, and comprehensively explored urbanization levels in the Bohai Rim using four measurement scale units: administrative division, land-sea location, terrain feature, and geomorphological type. Given the difficulty of obtaining high quality, multi-temporal Landsat TM/ETM+ data for the 44 cities in the Bohai Rim region, and the cost of extracting urban land use information from Landsat TM/ETM+ data of these cities for the four different time periods, we did not evaluate the accuracy of extracted built-up urban areas of all cities in the Bohai Rim. Instead, we used only the Landsat TM/ETM+ data of Beijing for the years 1992, 1998, 2006, and 2012 to conduct the accuracy assessment. The use of more Landsat TM/ETM+ images of other cities to evaluate the accuracy of extracted urban areas would make our conclusions much more convincing. However, it should be noted that this study has succeeded in measuring the urbanization level in a fast, efficient, and multidimensional way using DMSP/OLS nighttime light data. It measured the level of urbanization in different locations and under different natural conditions. This can provide data support when analyzing the progress of urbanization and can facilitate discovery of potential land issues in different places, and therefore helps to provide suggestions on future directions and paces of urban expansion in the Bohai Rim. It also provided a methodology and technical support for measuring urbanization at the national level for a long time series. This will facilitate regulation of wide areas, even nationwide urban land use patterns, and promote healthy and harmonious urbanization in China.

6 Conclusions

We evolved a human–computer interactive boundary correction method to determine built-up urban areas and subsequently proposed a method for measuring levels of urbanization based on DMSP/OLS nighttime light data. To comprehensively measure the level of urbanization in the Bohai Rim region from 1992 to 2012, we established four different measurement scale units, namely, administrative division, land and sea location, terrain feature, and geomorphological type. Our major findings were as follows.

First, the extraction results based on DMSP/OLS nighttime light data showed substantial agreement with those based on Landsat TM/ETM+ data on spatial patterns, with an average overall accuracy of 97.70% and an average Kappa coefficient of 0.79. This finding demonstrated a high level of reliability of the extraction results that could well reflect the actual status of built-up urban areas in the region.

Second, the Bohai Rim's urbanization level has increased annually, demonstrating a significant growth rate during the period from 1998 to 2006. The urbanization level of the Beijing–Tianjin–Hebei urban agglomeration was always higher than that of the entire Bohai Rim region, while the urbanization level of the Shandong Peninsula urban agglomeration showed a marked increase, exceeding the level of the Beijing–Tianjin–Hebei urban agglomeration in 2002. Areas with high urbanization levels have evidenced movement from capital to coastal cities, indicating a spatial characteristic of being located close to the coast.

Third, the distribution of the built-up urban areas showed a certain degree of zonal variation. The urbanization level was negatively correlated with relief amplitude and altitude. A high level of urbanization was found in low altitude platforms and low altitude plains, with a gradually narrowing of the gap between these two geomorphological types.

Fourth, based on comprehensive measurements and results of multiscale units of the urbanization level of the Bohai Rim, we conclude that in the foreseeable future, low altitude hills—especially those at altitudes between 50 m and 150 m, and with reliefs ranging from 30 m to 200 m—will be key areas of urban construction in the region. The pace of urbanization in low altitude platforms, especially in locations below 50 m should be reduced.

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