How does the urbanization level change in the Yangtze River economic belt, China? A multi-scale evaluation using DMSP/OLS nighttime light data

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Abstract. Based on DMSP/OLS nighttime light data, we select the Yangtze River Economic Belt (YREB) as the research area to evaluate the urbanization level of the YREB at provincial, regional, and county scales. First, we construct the compounded night light index (CNLI) based on the nighttime light data by extracting the integrated light intensity (I) and the built-up area (S) of the Yangtze River economic belt from 1992 to 2012, and we respectively calculate the CNLI of the YREB at the province, regional and county scales of the YREB such that we can comprehensively analyze the spatial and temporal distribution characteristics and dynamic changes of the process of urbanization in the YREB. Second, we construct two traditional urbanization level evaluation index models based on socio-economic statistics: The integrated urbanization level index model (IU) and the urbanization composite index model (Cf), which are used to respectively calculate the urbanization levels at the province, region, and county scales of the YREB. Finally, we establish a multi-scale urbanization model of CNLI, IU, and Cf in order to perform correlation analysis of CNLI, IU, and Cf on different scales. The results show that CNLI can objectively reflect the development status of urbanization level, and provide a new index and method for better monitoring the state of urban development and evaluating the annual change of urbanization.

1. Introduction
As the first “golden waterway” in China, the YREB stretches across three major regions in eastern, western, and central China. With the active promotion of urbanization by various provinces and municipalities in the Yangtze River Basin, three major urban agglomerations, including the Yangtze River Delta (YRD: including Shanghai, Jiangsu, and Zhejiang), the Central Yangtze River (CYR: including Hubei, Hunan, and Jiangxi) and Cheng-Yu (CY: including Sichuan and Chongqing) [1], as well as some relatively strong central cities, have already been formed. However, the urbanization of the YREB faces some problems. For example, a large number of small towns are dispersed; the development of urbanization lags obviously behind that of industrialization [2]. Therefore, it is of great significance to carry out a dynamic assessment of the urbanization level of the YREB and to
analyze the time and space differences of the urbanization process in making scientific decisions in the region and the sustainable development of the YREB. At present, the integrated index method [3] and composite index method [4] are mostly used to measure the level of urbanization in many studies on urbanization measurement. Nevertheless, there are still 3 main deficiencies of the traditional evaluation index. First, the traditional urbanization measurement method relies on socio-economic statistics, which are usually time-consuming and laborious. Second, the statistical caliber of indicators is not completely consistent, resulting in the limitations of traditional urbanization evaluation methods. Third, the research scale is limited to the administrative unit, which results in the lack of spatial characteristics of urbanization. The current research mainly focuses on the national, provincial and municipal levels [5].

Nighttime light remote sensing data can reflect the characteristics of human activities. Because of its macro, spatial and continuous characteristics, it has become a new type of data for large-scale urbanization research and has been widely concerned about [6]. Croft [7] first proposed using the DMSP/OLS to extract urban built-up areas, after which numerous scholars began relevant researches. In terms of urbanization information extraction, Chen [8] and Zhuo [9] are relatively classic, providing the additive lighting index constructed for the first time by using DMSP/OLS nighttime light data to estimate the level of urbanization in China’s provinces. As far as population estimation is concerned, Yu [10] used time-series DMSP/OLS nighttime light imagery to monitor the population evolution in China from 2000 to 2010. In economic terms, Wang [11] proposes a new enhanced light intensity model (ELIM) to estimate the gross domestic product (GDP) for sub-national units within Uganda. Currently, nighttime light data are mainly used in urban size and urban expansion [12], poverty evaluation [13], environment [14], disasters [15], energy [16], and other fields, which have good prospects for development.

In view of the shortcomings of the traditional urban level evaluation index method, this paper selects the YREB as the research area, constructing a comprehensive light index model (CNLI) with DMSP/OLS nighttime light data from 1992 to 2012 as the data source. On this basis, in order to verify the effectiveness of the CNLI, this paper also builds two traditional urbanization level evaluation index models based on statistical data: the integrated urbanization level index model (IU) and the urbanization composite index model (Cf). The three methods of CNLI, IU and Cf were used to analyze the dynamic urbanization level at different levels in the YREB, and to explore the advantages and disadvantages of the comprehensive light index model and different traditional evaluation methods in measuring the urbanization level of the YREB, to better promote the development of urbanization in the YREB.

2. Materials and methods

2.1. Study area

![Location of Yangtze River Economic Belt](image)
The Yangtze River Economic Belt (YREB) is located between 97° 36' -122° 95' E and 21° 14' -35° 12' N, which covers 9 provinces and 2 municipalities of China (Figure 1). The YREB covers an area of approximately 2.05 million square kilometers, accounting for 21.7% of China’s land area [17]. In 2018, there are 130 cities in the YREB, including 9 megacities with urban populations over 5 million, 77 large cities with urban populations over 1 million, 34 medium cities with urban populations over 0.5 million and 10 small cities with urban populations lower than 0.5 million [18].

2.2. Data resources

2.2.1. DMSP/OLS nighttime data. The DMSP/OLS stable nighttime lighting dataset (https://ngdc.noaa.gov/eog/dmsp) from 1992 to 2012 used in this paper was released by the National Geophysical Data Center. The dataset is monitored by six DMSP/OLS satellites and effectively reflects nighttime light information in cities and human settlements [19]. In this research, we use the system of revised nighttime data for China, and the data itself is from the Beijing Normal University Human and Environment System Center for Sustainable Research.

2.2.2. Socio-economic statistics. The research object of this paper is the urbanization level of all the municipal districts and county-level areas under the jurisdiction of the 9 provinces and 2 municipalities in the YREB in China from 1992 to 2012. We collected relevant socio-economic statistical indicators in all regions separately; data are from the statistical yearbooks and statistical data at all levels of the 9 provinces and 2 municipalities directly under the Central Government for the three years of 1993, 2003 and 2013, as well as “The Statistical Yearbook of China’ s Cities”, “The Statistical Yearbook of China’ s Counties”, the “Regional Economic Statistical Yearbook” and other national statistical yearbooks.

2.3. Method

2.3.1. Urbanization level dynamic analysis method based on nighttime light data. In this research, we use the compounded night light index (CNLI) proposed by Gao et al. [20] to evaluate the urbanization level of cities at different scales in the YREB. The CNLI refers to the region of light pixel total brightness value and the maximum possible total brightness value ratio, the reaction zone light intensity level. Based on the CNLI index, we analyzed the dynamic changes of urbanization levels in 1992-2002 and 2002-2012 on the three scales of provinces, regions and counties, respectively. In this paper, the urbanization level dynamic index (U) is used to reflect the average annual increment of CNLI.

\[
CNLI = I \times S = \frac{1}{N_L \times DN_M} \sum_{i=p}^{DN_M} (DN_i \times n_i) \times \frac{Area_N}{Area}
\]

\[
U = \frac{CNLI^{t+M} - CNLI^t}{M}
\]

where, \(I\) is the integrated light intensity, and it represents the average lighting intensity of urban lighting pixels. \(S\) is the built-up area, which means the ratio of urban light pixel area to total area. \(DN_i\) is the gray value of the \(i\)-gray urban light pixel, \(n_i\) is the total number of the \(i\)-gray urban light pixels, \(P\) is the optimum threshold for extracting the urban land information, and \(DN_M\) is the urban light pixel (The maximum gray value in this study is 63), \(N_L\) is the number of urban lighting pixels satisfying the condition of \(DN_M \geq DN \geq P\). \(U\) represents the average annual increase in night light index, \(CNLI^t\) and \(CNLI^{t+M}\), respectively, represents the \(t\), \(t+M\) year’s light index.

2.3.2. Traditional urbanization level dynamic evaluation method. Based on the composite index method of traditional research methods, we established two kinds of the most common dynamic evaluation models of urbanization level: The integrated urbanization level index model (IU) [3] and the urbanization composite index model (CI) [4].
Integrated urbanization index model (IU). According to the connotation and essential characteristics of urbanization, this paper proposes an integrated urbanization level index model \((IU)\) that covers three dimensions of urbanization: population urbanization \((PU)\), economic urbanization \((EU)\) and spatial urbanization \((SU)\). The integrated model is

\[
IU = W_{PU} \times PU + W_{EU} \times EU + W_{SU} \times SU
\]

(3)

Where \(W_{PU}, W_{EU}, W_{SU}\) are the weights of \(PU, EU\) and \(SU\). The weights of the three urbanization components in this paper are given, respectively, as \(W_{PU} = 0.4, W_{EU} = 0.35\) and \(W_{SU} = 0.25\) [3].

Urbanization composite index model \((Cf)\). We choose five statistical indicators that reflect the level of urbanization: the proportion of land for urban construction \((C_1)\), the share of the non-agricultural population in the total population \((C_2)\), the population density \((C_3)\), the proportion of the secondary and tertiary industries in GDP \((C_4)\) and the per capita gross domestic product \((C_5)\). To obtain the urbanization composite index model \((Cf)\). The weights were 1/6, 1/6, 1/6, 1/6, and 1/3, respectively [4].

\[
Cf = \sum_{i=1}^{5} W_i \times C_i
\]

(4)

3. Results

3.1. Dynamic evaluation of urbanization level based on nighttime light data

Seen from the nighttime light index from 1992 to 2012 (Table 1), the level of urbanization in the YREB has continued to increase from 1992 to 2012. Meanwhile, the average annual increase of \(CNLI\) from 1992 to 2002 is higher than that from 2002 to 2012, indicating the process of urbanization is accelerating.

| Year | 1992 | I | S | CNLI | 2002 | I | S | CNLI | 2012 | I | S | CNLI |
|------|------|---|---|------|------|---|---|------|------|---|---|------|
| Shanghai | 0.4508 | 0.1026 | 0.0463 | 0.5255 | 0.2652 | 0.1394 | 0.5877 | 0.3850 | 0.2263 |
| Yunnan | 0.4258 | 0.0002 | 0.0001 | 0.3980 | 0.0024 | 0.0010 | 0.4178 | 0.0064 | 0.0027 |
| Sichuan | 0.3973 | 0.0003 | 0.0001 | 0.3833 | 0.0035 | 0.0013 | 0.4212 | 0.0085 | 0.0036 |
| Anhui | 0.3202 | 0.0020 | 0.0006 | 0.3352 | 0.0105 | 0.0035 | 0.4253 | 0.0320 | 0.0136 |
| Jiangsu | 0.2724 | 0.0073 | 0.0020 | 0.3208 | 0.0470 | 0.0151 | 0.4567 | 0.1542 | 0.0704 |
| Jiangxi | 0.3012 | 0.0008 | 0.0002 | 0.2983 | 0.0041 | 0.0012 | 0.3271 | 0.0133 | 0.0044 |
| Zhejiang | 0.2445 | 0.0020 | 0.0005 | 0.2681 | 0.0183 | 0.0049 | 0.3434 | 0.0704 | 0.0242 |
| Hubei | 0.2748 | 0.0001 | 0.0006 | 0.2776 | 0.0054 | 0.0015 | 0.3160 | 0.0112 | 0.0035 |
| Hunan | 0.2670 | 0.0001 | 0.0003 | 0.2702 | 0.0040 | 0.0011 | 0.3019 | 0.0135 | 0.0041 |
| Guizhou | 0.3740 | 0.0002 | 0.0001 | 0.3604 | 0.0010 | 0.0004 | 0.3818 | 0.0037 | 0.0014 |
| Chongqing | 0.3577 | 0.0016 | 0.0006 | 0.3425 | 0.0044 | 0.0015 | 0.3825 | 0.0128 | 0.0049 |

From the perspective of provinces in the YREB, the differences in urbanization rates among different provinces and autonomous regions are significant. The overall trend is centered in Shanghai and Jiangsu Provinces, decreasing from the eastern coast to the western inland regions (Figure 2 (a)). The urbanization in Shanghai was the fastest in 1992-2002, with average annual increments of \(CNLI\) of \(9.31 \times 10^{-3}\). From 2002 to 2012, all provinces are in the stage of accelerated growth, with the rapid development in the YRD, driving the development of cities in the surrounding areas. With Chongqing affected by the strategy of the CY, the average annual increase of \(CNLI\) reached \(3.39 \times 10^{-3}\). Guizhou Province is still at a relatively low level in its urbanization (Figure 2 (d)).

At the regional level, the main feature is that the YREB takes the developed metropolis as the development center, driving the coordinated development of the surrounding urban areas. From 1992-2002, the urbanization rate of big cities such as Shanghai, Suzhou and Chengdu increased significantly, with the average annual growth rate of \(CNLI\) being \(3.0 \times 10^{-3}\). These are followed by Hefei, Wuxi, Nanjing, Nanchang, Wuhan and Kunming, with an average annual increase of over \(1.0 \times 10^{-3}\) in \(CNLI\).
(Figure 2 (b)). From 2002 to 2012, the level of urbanization witnessed a substantial increase. The most rapid development has taken place in the eastern coastal cities of Suzhou, Wuxi, Shanghai, Jiaxing and Hefei. The radiation effect has been brought into full play to promote the development of a large range of surrounding areas. The number of cities whose CNLI average annual increase is more than $1.0 \times 10^{-3}$ in urban areas is 31, representing an increase of 16 over the previous 10 years (Figure 2 (e)).

Figure 2. The average annual increase of CNLI in different stages of the YREB. ((a), (b) and (c) respectively represent the average annual increase of CNLI at provincial, regional and county levels from 1992 to 2002; (d), (e) and (f) respectively represent the average annual increase of CNLI at provincial, regional and county levels from 2002 to 2012.).

At the county level, there has been a substantial increase from 2002 to 2012 compared with 1992 to 2002, with the developed districts and counties primarily driving the urbanization in the surrounding districts and counties. Moreover, the regions that lagged behind in their development have also entered a period of steady and accelerated growth. From 1992 to 2002, there are 140 counties whose annual average increase of CNLI exceeds the average level of the YREB, of which 52.86% (74 counties) were located in the YRD (Figure 2 (c)). From 2002 to 2012, there are 157 counties whose annual average increase of CNLI exceeds the average level of the YREB, of which 52.87% (83 counties) were located in the YRD (Figure 2 (f)).

3.2. Dynamic evaluation of urbanization based on traditional methods
Based on the socio-economic statistics from 1992 to 2012, this paper calculates the $IU$, $C_f$ and individual urbanization indicators of 9 provinces and 2 municipalities in the YREB. The classification maps of $IU$ and $C_f$ at provincial, regional, and county levels were drawn based on ArcGIS spatial analysis function (Figure 3). The classification standard we use is adjusted based on natural breaks. As seen from Figure 3, $IU$ and $C_f$ based on statistical data differ in their evaluation of the urbanization level at all levels, but both reflect the same overall trend. The provincial scale is characterized by the rapid development of the eastern coastal areas, the balanced development of the central region, and the slow development of the western region. At the regional level, the capital cities at the municipal scale maintained a rapid growth rate, higher than that of other cities. As time goes by, various regions around the capital city formed rapid developed urban agglomerations, such as the
YRD centered on Shanghai, the CYR centered on Wuhan, and the CY centered on Chongqing and Chengdu, and these urban agglomerations drive the development of the surrounding areas. The county level reflects the level of urbanization in all regions more accurately. Based on the above analysis, the urbanization level of each scale of the YREB based on the traditional composite index method is the same as the trend reflected by CNLI.

In addition to reflecting the same characteristics of regional urbanization at the provincial and municipal levels, the map also demonstrates the development of other districts and counties, except for the provincial capitals. According to the development of the districts and counties around the provincial capital, the provincial capitals can be compared regarding their strength in driving the development of the surrounding areas. For example, it can be seen from the figure that the number of high-growth counties around Shanghai, Nanjing, Wuhan and Chongqing grew faster than those of Changsha, Guiyang, Kunming and Nanchang over time, indicating that the intensity of driving development around these districts and counties is even greater.

![Figure 3](image)

**Figure 3.** Integrated Urbanization (IU) and Composite Index (Cf) at the provincial, regional, and county levels in 1992, 2002 and 2012. (a)-(f) respectively represent IU and Cf at the provincial level in 1992, 2002 and 2012; (g)-(l) respectively represent IU and Cf at the regional level in 1992, 2002 and 2012; (m)-(r) respectively represent IU and Cf at the county level in 1992, 2002 and 2012.

### 4. Discussion

#### 4.1. Correlation analysis on evaluation indexes of urbanization level

**Table 2.** The correlation analysis of nighttime light data and traditional urbanization statistical indicators at the provincial, regional, and county levels.

| Scale      | Index | C1    | C2    | C3    | C4    | C5    | Cf   | IU   |
|------------|-------|-------|-------|-------|-------|-------|------|------|
| Provincial | I     | 0.810 | 0.597 | 0.798 | 0.520 | 0.580 | 0.649 | 0.701|
| level      | S     | 0.972 | 0.773 | 0.972 | 0.877 | 0.865 | 0.922 | 0.925|
|            | CNLI  | 0.989 | 0.756 | 0.988 | 0.839 | 0.818 | 0.887 | 0.912|
| Regional   | I     | 0.652 | 0.620 | 0.512 | 0.266 | 0.628 | 0.636 | 0.579|
| level      | S     | 0.973 | 0.783 | 0.683 | 0.608 | 0.881 | 0.892 | 0.842|
|            | CNLI  | 0.979 | 0.793 | 0.669 | 0.607 | 0.894 | 0.904 | 0.849|
| County     | I     | 0.471 | 0.371 | 0.429 | 0.339 | 0.345 | 0.390 | 0.462|
| level      | S     | 0.790 | 0.354 | 0.699 | 0.398 | 0.607 | 0.665 | 0.533|
|            | CNLI  | 0.870 | 0.382 | 0.781 | 0.391 | 0.607 | 0.679 | 0.567|
From three levels of provinces, regions and counties to study, we selected 9 provinces, 2 municipalities, 44 regions and 460 counties to calculate nighttime lighting data (I, S and CNLI) and the traditional urbanization level factor (Cf), integrated urbanization level index (IU) and urbanization composite index (CF) in 2012. The results of the correlation analysis of the two methods are shown in Table 2.

The analysis results reveal that there is a significant correlation between nighttime light data and the urbanization level calculated by the traditional method, as follows:

1. On the whole, the correlation coefficient of the provincial scale is higher than that of the region and county levels, which reflects the macro characteristics of nighttime light data. Among them, 93.65%, 76.19% and 92.06% of the provincial, regional and county level factors passed the test of significance level 0.001. It indicated that CNLI can be used as an index to evaluate the urbanization level.

2. Among the three indicators CNLI, I and S, the correlation of I is relatively weak. S and CNLI are significantly related to the statistical indicators at the provincial, regional and county levels. Moreover, the values of S and CNLI are close to each other, indicating that CNLI is more affected by S.

3. Compared with other traditional indicators, the three indicators of CNLI, S and I have the highest correlation with the proportion of urban construction land C1 (space urbanization), indicating that the planar expansion of urban areas is well-reflected. The correlation between the three indexes and C2 and C3 (population urbanization) is second. The correlation between C2 and C3 (economic urbanization) is the weakest, which shows that CNLI does not clearly reflect the level of economic urbanization in the YREB. Both Cf and IU are significantly related to CNLI, but the correlations are different.

4.2. Deficiencies and prospects

The OLS sensor on DMSP provides the world’s longest time series of nighttime light observation data from 1992 to 2014. However, there are still some problems, such as low resolution (about 1km) and data supersaturation. Currently, NPP/VIIRS is a new type of nighttime light data released by the National Geophysical Data Center of NOAA, which has higher sensitivity to nighttime light. In addition, the nighttime light data of Luojia-1, which is independently developed by China, has a resolution of 130m, which can better reflect the dynamic changes of urbanization level. In future research, we can use the NPP and Luojia-1 nighttime light data from 2013 to 2020 to construct a long-time series of night light index to evaluate the urbanization level of the YREB in different scales under the long time series.

5. Conclusions

Based on DMSP/OLS nighttime light data, we build the light index model CNLI and two traditional urbanization evaluation methods to compare and evaluate the urbanization level of YREB at different scales from 1992 to 2012. We found that CNLI based on nighttime light data was significantly correlated with IU and Cf based on socio-economic statistics at provincial, municipal and county levels. Although there are some differences between the two traditional methods in evaluating the urbanization level of the YREB, they both reflect the same general trend of spatial-temporal change of urbanization level. The feasibility of the CNLI to be evaluated at any spatial scale is verified by both methods. Influenced by subjective factors, there are differences in index selection and index weight between the two traditional methods, which leads to differences in the final evaluation of the urbanization level. This is the inevitable limitation of traditional methods. Compared with the conventional methods, CNLI can better reflect the influence of the spatial attribute index, population attribute index and economic attribute index on the urbanization level, and overcomes the influence of human factors, poor timeliness, high cost and other problems. At the same time, CNLI has overcome the limitation of statistical analysis of administrative units. For some undeveloped areas lacking statistical data, CNLI can objectively reflect the development status of urbanization level. Generally
speaking, the nighttime light data provides a new index and method for better monitoring the state of urban development and evaluating the annual change of urbanization.

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