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Quantitative estimation of urbanization dynamics using time series of DMSP/OLS nighttime light data: A comparative case study from China's cities

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ABSTRACT

Urbanization process involving increased population size, spatially extended land cover and intensified economic activity plays a substantial role in anthropogenic environment changes. Remotely sensed nighttime lights datasets derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) provide a consistent measure for characterizing trends in urban sprawl over time (Sutton, 2003). The utility of DMSP/OLS imagery for monitoring dynamics in human settlement and economic activity at regional to global scales has been widely verified in previous studies through statistical correlations between nighttime light brightness and demographic and economic variables (Elvidge et al., 2001; Ghosh et al., 2010). The quantitative relationship between long-term nighttime light signals and urbanization variables, required for extensive application of DMSP/OLS data for estimating and projecting the trajectory of urban development, however, are not well addressed for individual cities at a local scale. We here present analysis results concerning quantitative responses of stable nighttime lights derived from time series of DMSP/OLS imagery to changes in urbanization variables during 1994–2009 for more than 200 prefectural-level cities and municipalities in China. To identify the best-fitting model for nighttime lights-based measurement of urbanization processes with different development patterns, we comparatively use three regression models: linear, power-law and exponential functions to quantify the long-term relationships between nighttime weighted light area and four urbanization variables: population, gross domestic product (GDP), built-up area and electric power consumption. Our results suggest that nighttime light brightness could be an explanatory indicator for estimating urbanization dynamics at the city level. Various quantitative relationships between urban nighttime lights and urbanization variables may indicate diverse responses of DMSP/OLS nighttime light signals to anthropogenic dynamics in urbanization process in terms of demographic and economic variables. At the city level, growth in weighted lit area may take either a linear, concave (exponential) or convex (power law) form responsive to expanding human population and economic activities during urbanization. Therefore, in practice, quantitative models for using DMSP/OLS data to estimate urbanization dynamics should vary with different patterns of urban development, particularly for cities experiencing rapid urban growth at a local scale.

1. Introduction

Occupying ~0.5% of Earth's land surface (Schneider et al., 2009), global urban areas hold approximately half of the current world population, and global urban population is projected to increase by more than 2 billion by 2050 (UN, 2010). As human-dominated habitats, urban areas therefore play a crucial role in anthropogenic environmental changes due to the effects of urban agglomeration in relating to high population density, intensive energy consumption and socio-economic activities (Johnson, 2001; Montgomery, 2008; Shukla and Parikh, 1992). Consequently, urban areas may profoundly affect climate and ecosystems locally and even globally by land cover conversion, increase in impervious surfaces and release of anthropogenic greenhouse gases and loss of biodiversity (Alberti, 2005; Folke et al., 1997; Pataki et al., 2006). Urbanization is a simultaneous process associated with demographic dynamics, socio-economic growth and land-use change and it is a salient human-induced force on environment and ecosystems. Measurement and monitoring of urban dynamics therefore are essential for understanding global urbanization and its environmental consequences in a changing world (Johnson, 2001; Shukla and Parikh, 1992).

Satellite-based observations with various spatial, temporal and spectral resolutions have been extensively applied in investigations of urban dynamics and the effects of urbanization on environment

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and ecosystems because remote sensing can provide timely and spatially explicit information for urbanization processes in comparison with census data. In most previous surveys, extensive use of remote sensing has been made of visible, near-infrared and radar sensors to delineate tempo-spatial changes in urban extent (Grey et al., 2003; Pacifici et al., 2008; Schneider et al., 2009, 2010; Sugumaran et al., 2002). Demographic and economic indicators for assessing urbanization, however, have rarely been connected to remotely sensed data. Therefore, enhanced abilities of satellite-based observation to obtain more comprehensive and timely characteristics relating to urban dynamics are needed to further understand anthropogenic changes in the Earth's landscape and their associated environmental consequences during the urbanization processes.

Nighttime light signals derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) provide striking remotely sensed data to analyze the relationship between urbanization and human-induced light emission (Elvidge et al., 1997; Small and Elvidge, 2010; Small et al., 2005; Sutton, 2003; Zhang and Seto, 2011). Although the initial purpose of DMSP/OLS was designed to observe the clouds illuminated by moonlight using two broad spectral bands: visible-near infrared (VNIR, ranged from 0.5 to 0.9 μm) and thermal infrared (TIR, ranged from 10.5 to 12.5 μm), DMSP/OLS images have been extensively used in urban studies due to the low-light sensing capabilities at night without moonlight (Elvidge et al., 1997, 1999). After excluding glare and sunlit data, the global map product of stable nighttime lights was composed of the spatially observed VNIR emission sources including human settlements, fishing boats, fires and gas flares (Elvidge et al., 2001). Long-term archives of DMSP/OLS nighttime imagery provide uniform, consistent and valuable data sources for investigating urban dynamics. The most notable advantage of DMSP/OLS nighttime light imagery is that the night light brightness have been utilized in several studies for quantitatively estimating and mapping socioeconomic activities related to the urbanization processes at regional to global scales. Sutton et al. (2001) estimated the global human population using the statistical relationship between nighttime lighted area and urban population. Sutton and Costanza (2002), Doll et al. (2000; 2006) and Ghosh et al. (2010) created regional and global disaggregated maps of gross domestic product (GDP), respectively, using statistical relationships between lit urban areas or nighttime radiance data and GDP based upon administrative units. Zhang and Seto (2011) used multitemporal DMSP/OLS nighttime lights data to estimate regional and global urban growth based on linear correlation between night light brightness and urban population. Amaral et al. (2005) found significant linear relationships between DMSP night light areas and population size and electric power consumption over Amazonia. Although previous studies differed slightly in their approaches and scopes, the results of these analyses commonly suggested that DMSP/OLS nighttime imagery could be indicative of urbanization-related socio-economic activity, particularly in the absence of census data (Ghosh et al., 2010).

Most previous studies have attempted to quantify the correlation between night lighting areas and detection frequencies in DMSP/OLS data and urbanization variables based upon a single temporal dataset derived from a set of cities. In these studies, enhanced night lights have been consistently associated with increased population size, urban land cover and economic activity (Amaral et al., 2005; Doll et al., 2006; Elvidge et al., 2001). But few studies have been concerned with the quantitative relationship between both long-term variations of DMSP/OLS nighttime light signals and urbanization-related socioeconomic parameters, which is desirable for quantitatively estimating temporal variations of urbanization processes via DMSP/OLS night light data, particularly for the studies of individual cities with limited administrative boundaries at a local scale. The objectives of this study are to quantify the relationship between stable nighttime light brightness and several urbanization variables over time and to test the capability of DMSP/OLS nighttime light data for estimating conspicuous urban expansion processes, like recent occurrences in China, at both country scale and local scale. We conduct a series of comparative statistical regression analyses for more than 200 China's cities involving linear, power law and exponential models in order to find the best-fitting model for creating quantitative relationships between several urbanization variables and remotely sensed nighttime light signals for different types of urban development trajectories.

2. Data and methods

2.1. Socio-economic dataset of urbanization for China's cities

As the most populous country, China is experiencing unprecedented urbanization with rapid economic growth over the past two decades (Deng et al., 2008; Zhang and Song, 2003). The 2010 population census shows that nearly half of the Chinese population live in urban areas, an increase of 13.5% since 2000 (National Bureau of Statistics of China, 2011). Increased urban land cover and population lead to a series of environmental and health consequences in China: urban heat islands (Li et al., 2004; Zhou et al., 2004), air pollution (Chan and Yao, 2008; He et al., 2002), enhanced greenhouse gases (Dhakal, 2009; Dong and Yuan, 2011) and increased health risk (Kan and Chen, 2004; Xu et al., 1994). Investigating the urbanization process and its influences in China therefore is crucial for sustainable development in the context of management issues and decision making. The primary challenge for estimating urbanization processes at a local scale via DMSP/OLS data is to obtain quantitative relationships between urbanization parameters and night light brightness across different types of urban development trajectories. We assembled a city-level statistical dataset consisting of several time series spanning 16 years (1994–2009): urban population, official purchasing power parity, GDP, urban built-up area and electric power consumption for 287 prefectural-level cities and municipalities in China (Fig. 1) derived from statistical yearbook of cities (National Bureau of Statistics of China, 1995–2010). According to National Bureau of Statistics of China, the administrative district of cities in which suburban districts are excluded is regarded as the statistical area of urban where the demographic and socioeconomic data were collected. In order to maintain the comparability of urbanization data over time within a city, 17 of 287 cities which show conspicuous changes in actual urban statistical areas during 1994–2009 were excluded from analyses.

2.2. Multi-temporal dataset of DSMP/OLS nighttime light

Version 4 of global DMSP/OLS nighttime lights time series of 1994–2009 (downloaded from URL of http://www.ngdc.noaa.gov/dmsp/download.html on June-21-2011) provide annual global composites of stable nighttime lights derived from the visible band. These images are composed of grid-based annual visible band digital numbers (DN) ranged from 0 to 63 with spatial resolution of 30 arc-seconds (approximately 1 km at the equator and 0.8 km at 40°N). The time series of DMSP/OLS nighttime lights for the period of 1994–2009 were collected by four individual sensors: F12 (1994–1999), F14 (1997–2003), F15 (2000–2007) and F16 (2004–2009). In order to reduce yearly variations and differences among sensors, we used the second order regression model provided by Elvidge et al. (2009) to empirically intercalibrate the annual nighttime light products to match the composite of F12 in 1999. We then choose the annual composites which show the best-fitting regression for years with two separate sensor composites of nighttime lights for analyzing the statistical relationships between intercalibrated DMSP/OLS data and urbanization variables.

It is well documented that the data of DMSP/OLS night lights may overestimate the spatial extent of human settlement owing to the effect of over-glow (Elvidge et al, 1997). Some previous studies therefore suggested the application of a low light threshold of detection frequency to reduce the overestimated spatial extent of lighted area (Imhoff et al., 1997). However, Small et al. (2005) assessed the relationship between over-glow and urban extent across 17 cities and

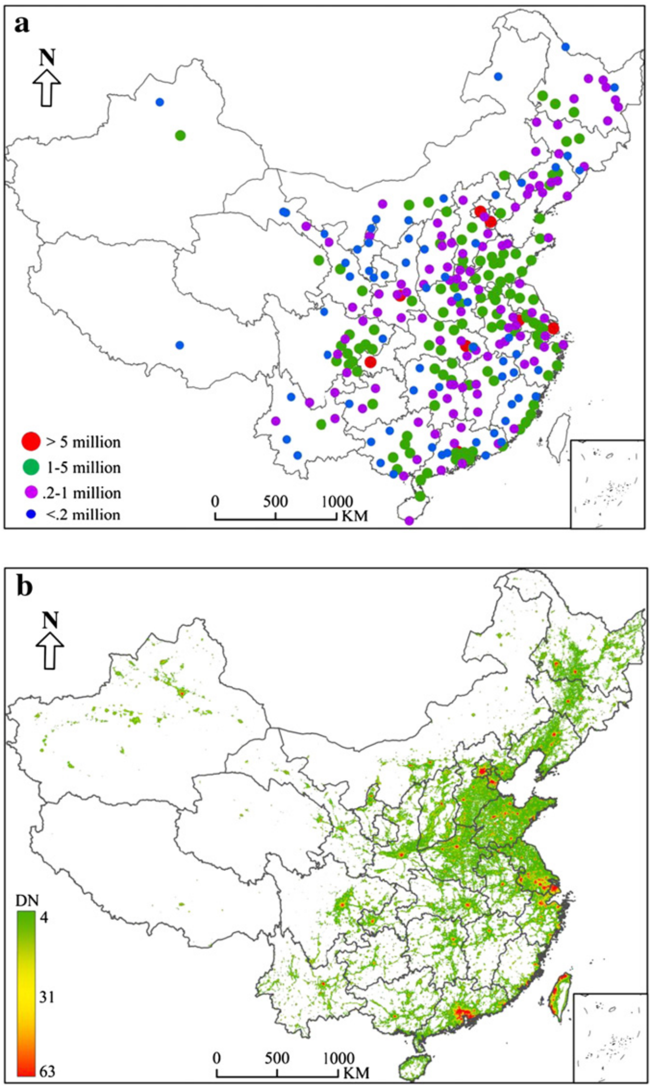

Fig. 1. a) Spatial distribution of China's prefectural-level cities and municipalities grouped by 2006 population size; b) spatial distribution of nighttime lights of China in 2006.

suggested that no single brightness threshold is valid to extract the urban extent for various cities. In this study, we used weighted light area, in which the spatial extent and brightness of nighttime light signals were jointly taken account into, to quantify the magnitude of nighttime light signals derived from intercalibrated DMSP/OLS images for China's cities from 1994 to 2009. Weighted light area is defined as the weighted sum of areas of lit pixels multiplied by the normalized DN value. For a given city, all pixels spatially contained within the administrative boundary of the city have been collected by overlaying the administrative unit map onto DMSP/OLS images based upon a uniform geo-reference system. We then calculated weighted light area by summing corrected pixel areas multiplied by the normalized DN. To reduce the effects of dim lights, usually caused by anthropogenic activities in undeveloped areas that were not taken into account in statistical data of urban development, all pixels with DN<12 (by comparisons with Landsat images and according to Small et al., 2011) were excluded from the calculation of weighted light area.

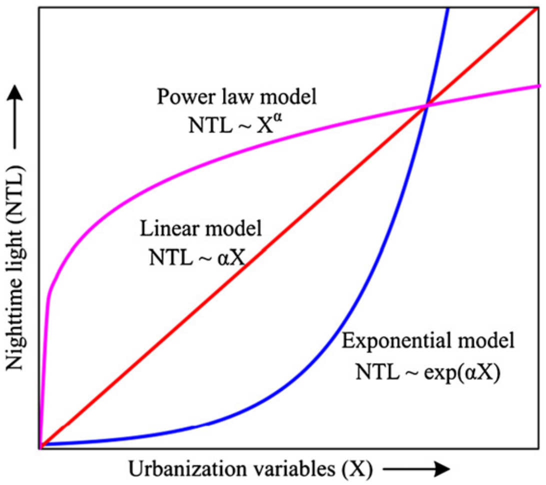

Fig. 2. Schematic diagram of three statistical models for delineating quantitative relationships between urbanization variables and DSMP/OLS nighttime light brightness.

2.3. Trend, correlation and regression analyses

Urbanization is a complicated natural social process accompanying simultaneous dynamics in demographics, the economy, materials and energy flows, and land cover. The primary challenge for estimating urban growth using satellite-based data is to find the association between remotely sensed signals and endogenous urbanization variables

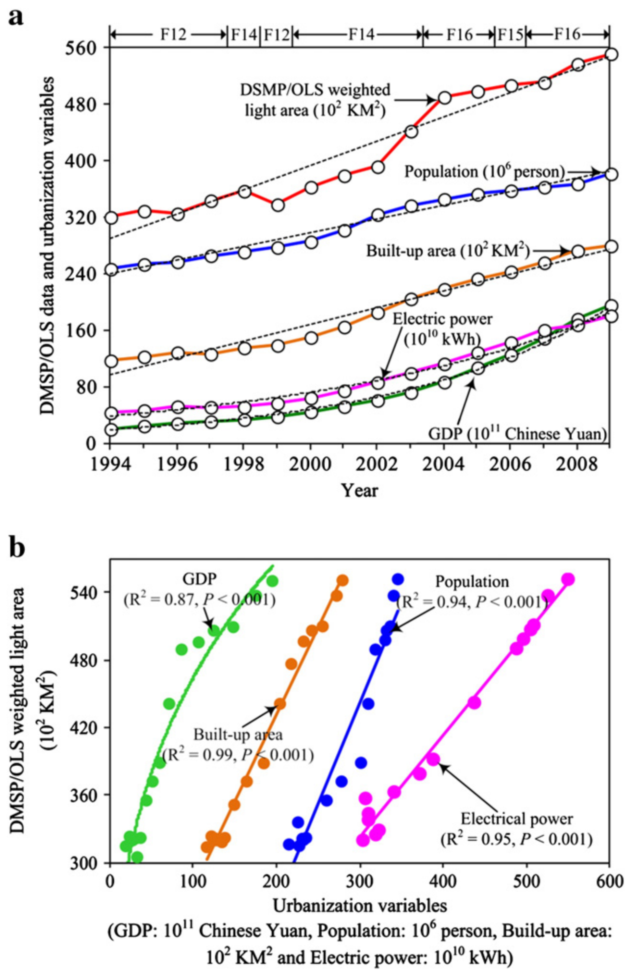

Fig. 3. a) shows comparisons of annual variations (solid lines) and long-term trends (dash lines) in urban population, urban land cover, electric power consumption, GDP and weighted nighttime light area for total values of China's prefectural-level cities and municipalities from 1994 to 2009 derived from statistical inventories and DSMP/OLS time series of images composed of data from 4 satellite sensors: F10, F12, F15 and F16; b) represents the statistical relationships between weighted nighttime light area and urbanization variables: GDP (according to power law model), built-up area, population and electric power consumption (according to linear model).

over time, particularly for estimates of changes in population and economic activity. Therefore, firstly we used the Mann–Kendall non-parametric test approach to examine whether there are conspicuous trends in time series of urbanization variables, which could be potentially connected to temporal changes in nighttime lights brightness. The significance test of Mann–Kendall trend analysis was performed by two-tailed t-test. Secondly, we used another non-parametric method, Spearman's rank correlation, to qualitatively examine the statistical dependence between nighttime light brightness and several synchronous urbanization variables. Spearman's Rho correlation coefficient (ranging from −1 to 1) was used to portray the overall monotonic relationship between urbanization variables and remotely sensed nighttime light signals over time. The statistical significance of Spearman's Rho was tested by two-tailed t-statistics. Combined results derived from both trend and correlation analyses could provide notable assessment regarding the utility of DMSP/OLS images for surveying urbanization processes in China's cities. In addition, we here reported statistical significances of trends and correlations as being greater than or less than the standard 0.05 cutoff without specific claims.

Different patterns of urbanization processes may vary with temporal trends in population size, urban land cover and economic-related parameters. We applied three simple statistical models (linear model, power-law model and exponential model) to fit the response of weighted nighttime lighting area to changes in the urbanization variables over time. As illustrated in Fig. 2, the linear model with a straight-line shape assumes a constant proportional response of nighttime lights to increases in urbanization variables. The power-law model with the convex shape ($0<\alpha<1$) was used to quantify dynamics of nighttime lights which may show gradually reduced response rate to escalated urbanization variables over time. This model may imply that nighttime light signal could gradually reach saturation for a given administrative boundary of a city. The exponential model with the concave shape ($\alpha>0$) was used to quantify a gradually increased response rate of nighttime lights to increased urbanization variables over time. Moreover, to obtain more reliable estimates, all samples (cities) with less than 10 years observational data were excluded from regression analysis. We estimated regression parameters of three models using the least squares method. The significance of regression was tested using t-statistics with the null hypothesis: the regression parameter is not significantly different from zero. The best-fitting model for quantifying the relationship between urbanization variable and nighttime light data were obtained by comparisons of coefficients of determination R^2, a measure of goodness-of-fit, and the root mean square error (RMSE) of different models.

3. Results and discussion

3.1. Country-level estimates

Statistically significant positive trends in urbanization variables across prefectural-level cities represent that China has been undergoing a rapid urbanization process since the 1990s (Fig. 3a). Different urbanization variables, however, show various temporal patterns: urban population shows distinct linear growth ($R^2=0.98$, $P<0.001$), marked increases in both urban GDP and urban electric power consumption can be characterized by exponential function with $R^2=0.99$ ($P<0.001$) and $R^2=0.97$ ($P<0.001$), respectively. The exponential function is also slightly better fit to the temporal trajectory of urban land cover ($R^2=0.98$, $P<0.001$) than linear model ($R^2=0.96$, $P<0.001$). In the meantime, although there exist annual fluctuations in time series of intercalibrated DMSP/OLS images owing to differences in satellite orbits and sensors, remotely sensed nighttime light signal across China's cities shows a significant linear trend towards increased weighted light area of human settlement ($R^2=0.93$, $P<0.001$). Consequently,

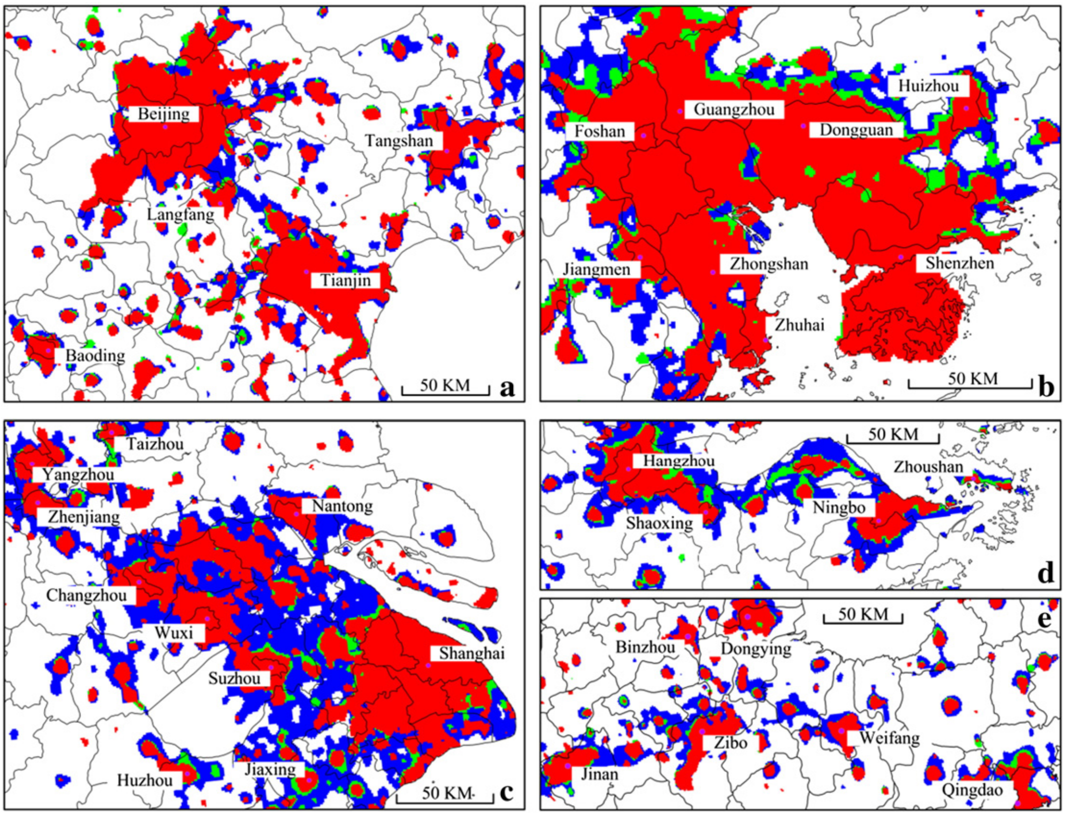

Fig. 4. Tempo-spatial changes in DSMP/OLS nighttime light area for China's cities located in five major metropolitan areas between 1996 (red), 2000 (green) and 2006 (blue): a) Beijing-Tianjin region; b) Pearl River Delta; c) Yangtze River Delta; d) Zhejiang province; and e) Shandong province. Administrative boundaries are drawn by solid curves.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

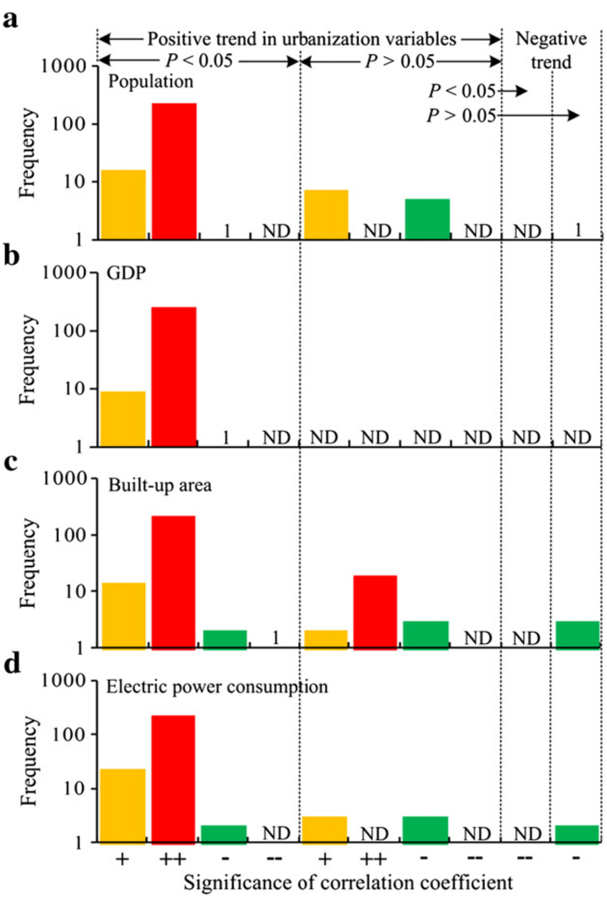

Fig. 5. Statistical distributions of Mann–Kendall trend tests for urban variables from 1994 to 2009 and Spearman's Rho rank correlation analyses for the statistical correlations between urbanization variables and DSMP/OLS nighttime lights. ND, no data (i.e. frequency = 0). ++ (−−): significantly positive (negative) correlation (95% confidence interval). + (−): positive (negative) correlation. The label of "1" stands for frequency = 1.

different temporal trends in both urbanization variables and DMSP/OLS images may lead to various responses of remotely sensed nighttime light signal to urbanization variables by different best-fitting models (Fig. 3b). These results may indicate that nighttime light signals derived from DMSP/OLS stable light imagery could be indicative of dynamics in urban extent, population and economic activity during salient urbanization processes in China at the country-level with various quantitative correlations with those urbanization variables.

3.2. Non-parametric analyses for individual cities

As shown in Fig. 4, spatially extended nighttime lit areas from the 1990's to the 2000's are prominent for almost all China's prefectural-level cities and municipalities resulted from prevalent urbanization processes at a local scale. Further statistical examinations are required for further verifying the capability of DMSP/OLS stable light imagery for assessing changes in urbanization variables within individual cities. Fig. 5 exhibits a statistical summary of non-parametric analyses for jointly estimating the long-term trends in four urbanization variables and the strength of statistical correlation with DMSP/OLS nighttime brightness of lights spanning 16 years (1994–2009). As shown in Fig. 5, significant increases in urban population are found in 94% of cities, and 93% of them display significant positive correlation between urban population and simultaneous dynamics in weighted nighttime light area. Almost 100-percent of cities show significant growth in urban GDP and 96% of them show strong positive correlation between urban GDP and nighttime weighted light area. A distinct trend towards increased urban built-up has occurred in 90% of cities of which 92% could be significantly associated to the changes in nighttime light signals. Moreover, 87% of cities show significant correlation between markedly rising urban electric power consumption and weighted nighttime lit area. These results indicate that changes in DMSP/OLS nighttime light signals could be statistically linked to synchronous dynamics in urbanization variables involving both spatial and socio-economic activity for most of China's cities. These findings provide a qualitative justification for applying the dataset of DMSP/OLS imagery to estimate urbanization processes at a local scale in China. In the following sections, the quantitative relationships between four urbanization variables and DMSP/OLS nighttime lights were obtained from the comparative analysis of three regression models for individual cities in China.

3.3. Estimates for urban population

Population is one of most frequently used indicators for estimating urbanization. Previous studies commonly suggest that increased urban population are most likely connected to spatially extended lighting area across both regionally (Amaral et al., 2005; Sutton, 2003) and globally (Zhang and Seto, 2011), mostly in linear proportion. As shown in Table 1 and Fig. 6, our results also display the predominantly linear relationship between two time series of urban population and nighttime light brightness. Sixty-seven percent of prefectural-level cities show increased weighted nighttime lit area within an administrative boundary is linearly proportional to growth in population size. A linear function could imply similar temporal trends in both urban population size and nighttime lights. In Shanghai City (Fig. 6b), for instance, annual increases in both variables were usually found to follow a robust

Table 1
Statistical summary of regression analyses of urbanization variables and DSMP/OLS nighttime lights for China's cities.

Variable	N[a]	Goodness-of-fit						The best-fitting model		
		Linear		Power-law		Exponential		LN[b]	POW[c]	EXP[d]
		$R^2>0.5$	$R^2<0.5$	$R^2>0.5$	$R^2<0.5$	$R^2>0.5$	$R^2<0.5$			
Population	250	184	66	180	70	183	67	167	21	62
GDP	252	206	46	226	26	203	49	82	167	3
Built-up area	239	163	76	ND[e]	ND	ND	ND	ND	ND	ND
Electric power	250	179	71	191	59	174	76	116	126	8

[a] The number of samples (cities) for regression analysis.
[b] Linear regression model.
[c] Power-law regression model.
[d] Exponential regression model.
[e] No data.

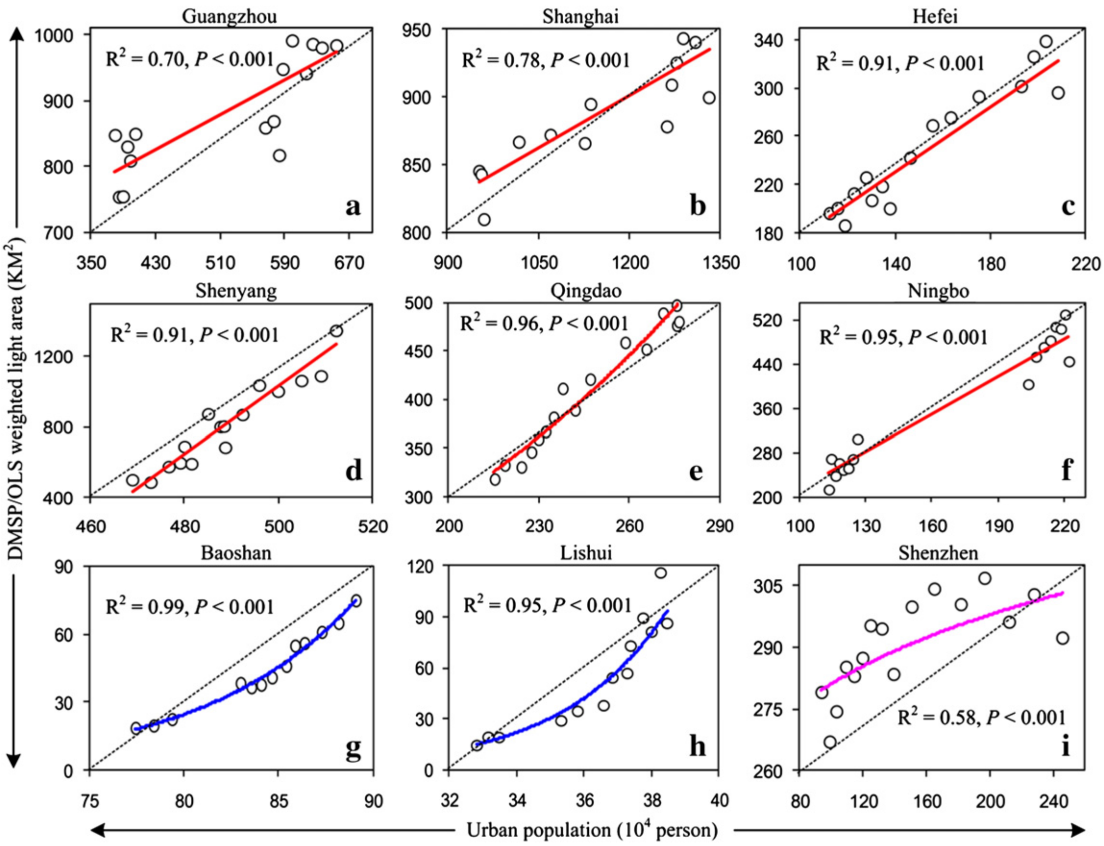

Fig. 6. Diverse responses of DSMP/OLS nighttime light signals to temporal changes in urban population from 1994 to 2009 by linear model (a-f), exponential model (g and h) and power law model (i) for nine China' cities.

power law function ($R^2=0.90$ with $P<0.001$ for urban population and $R^2=0.70$ with $P<0.001$ for weighted lit area). Hefei City (Fig. 6c) shows significant exponential increases in both urban population ($R^2=0.97$, $P<0.001$) and weighted lighting area ($R^2=0.86$, $P<0.001$). In 25% of China's cities, however, growth in nighttime light brightness distinctly exceeds increase in urban population size, such as in Baoshan City (Fig. 6g) and Lishui City (Fig. 6h) in which the quantitative relationship between both variables could be fit by exponential curves. This result may imply that other urbanization variables instead of population could be dominant factors in driving increases in DMSP/OLS nighttime light signals in these cities. In Shenyang City (Fig. 6d), for instance, weighted nighttime light area shows a significant exponential increase ($R^2=0.98$, $P<0.001$) and is in accordance with urban GDP and urban built-up area, in which distinct exponential increases have been identified with $R^2=0.98$ ($P<0.001$) and $R^2=0.95$ ($P<0.001$), respectively, while urban population shows a linear increase ($R^2=0.99$, $P<0.001$) from 1994 to 2009. Only a few cities (8%) show the power law function could be the best-fitting model for the relationship between population and nighttime lights, such as Shenzhen City (Fig. 6i), where the growth rate in urban population (by an exponential function with $R^2=0.99$ and $P<0.001$) largely exceeds the growth rate of urban nighttime light brightness (by a power law function with $R^2=0.63$ and $P<0.001$).

3.4. Estimates for urban economic activity

Previous studies have revealed a statistically significant positive linear relationship between regional-level nighttime light brightness and official measures of economic activity (i.e. GDP) (Doll et al., 2006; Elvidge et al., 2001; Ghosh et al., 2010). DMSP/OLS imagery therefore has been used to map global and regional distributions in economic activity (Doll et al., 2006; Ghosh et al., 2010). But for long-term series at a local scale, as illustrated in Fig. 7, our results suggest different quantitative responses of nighttime light brightness to changes in urban GDP for individual cities. 33% of China's cities (Table 1) show marked trends towards increased weighted nighttime light area in linear proportion to synchronously rising urban GDP, like Jinan City (Fig. 7g) which shows significant exponential increase in both GDP ($R^2=0.98$, $P<0.001$) and weighted light area ($R^2=0.97$, $P<0.001$) from 1994 to 2009. Particularly noteworthy, power-law responses of weighted lit area to urban economic activity occur in 66% of China's cities (Table 1). The implication of power-law responses for assessing urban economic activity using DMSP/OLS is temporal-lagging expansion of nighttime lighted area compared with relatively faster enhancement in the economy. In Nanjing City (Fig. 7b), for instance, urban GDP exhibits a striking exponential growth with $R^2=0.99$ ($P<0.001$) from 1994 to 2009 while weighted nighttime lit area show linear growth ($R^2=0.79$, $P<0.001$). In fact, significant exponential growth (with $R^2>0.5$ and $P<0.001$) in official measures of urban economic activity for the period of 1994–2009 has been identified in approximately one-hundred percent of China's prefectural-level cities. Various quantitative relationships between urban GDP and DMSP/OLS nighttime light signals, however, may indicate diverse underlying patterns of urban development in recent rapid urbanization processes in China. Thus, statistical models for DMSP/OLS nighttime light-based estimation of dynamics in urban economic activity at a local scale should be chosen based upon individual patterns of urban development.

3.5. Estimates for urban land cover

Urban extent can be directly linked to spatially lighted area derived from DMSP/OLS images. However, the primary problem is that nighttime lit area may overestimate the actual spatial extent of high density impervious urban land cover owing to the over-glow effect of artificial

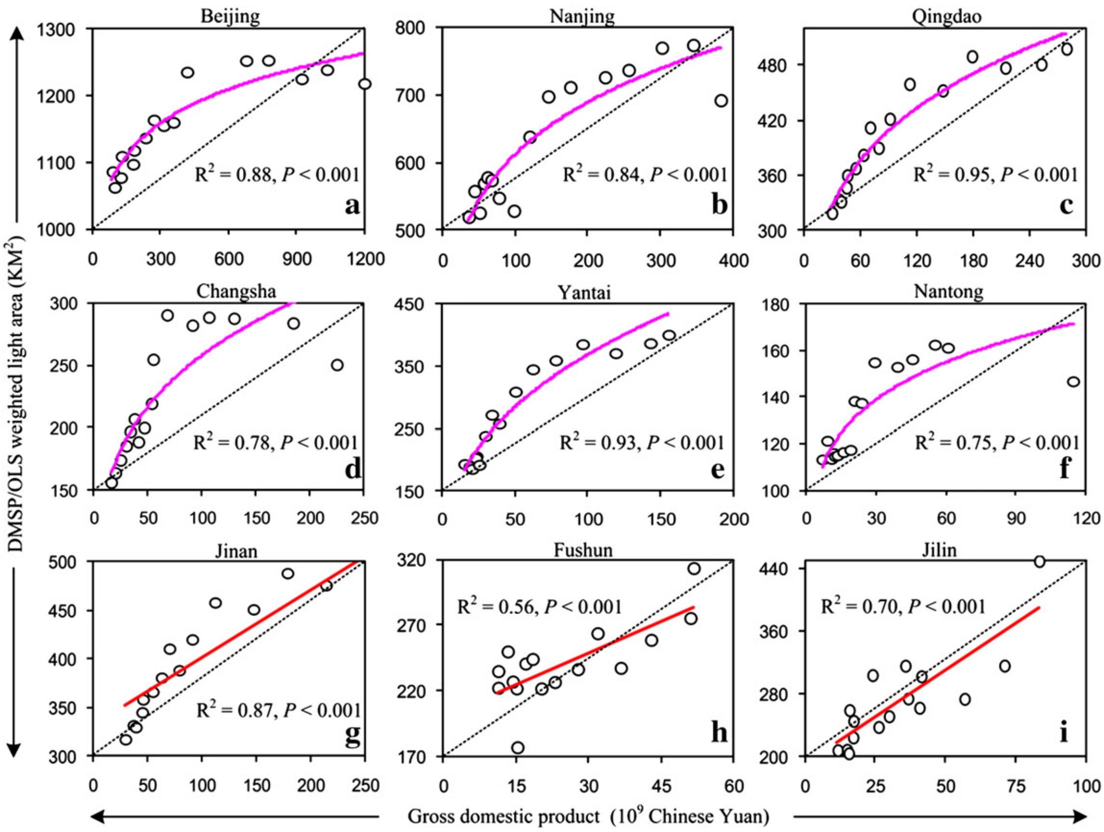

Fig. 7. Diverse responses of DSMP/OLS nighttime light signals to temporal changes in urban GDP from 1994 to 2009 by power-law model (a–f), linear model (g–i) for nine China' cities.

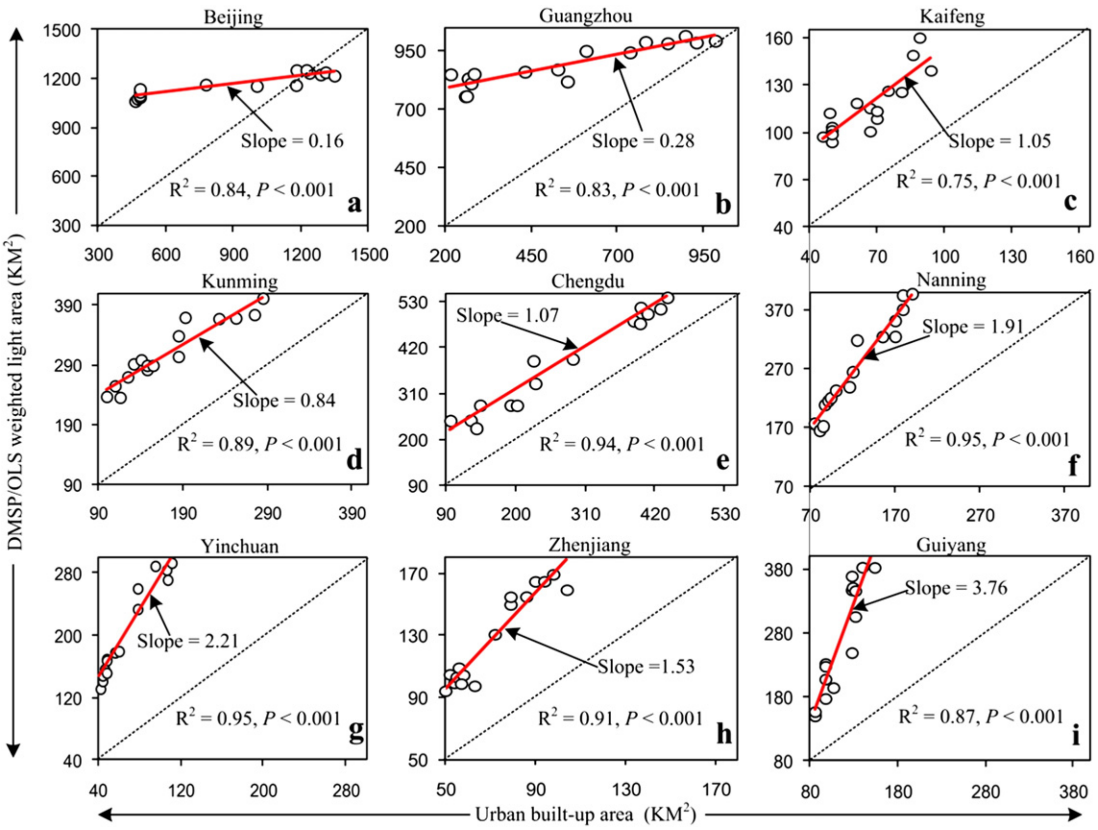

Fig. 8. Linear relationships between two time series of DSMP/OLS nighttime light signals and urban land cover from 1994 to 2009 for nine China' cities.

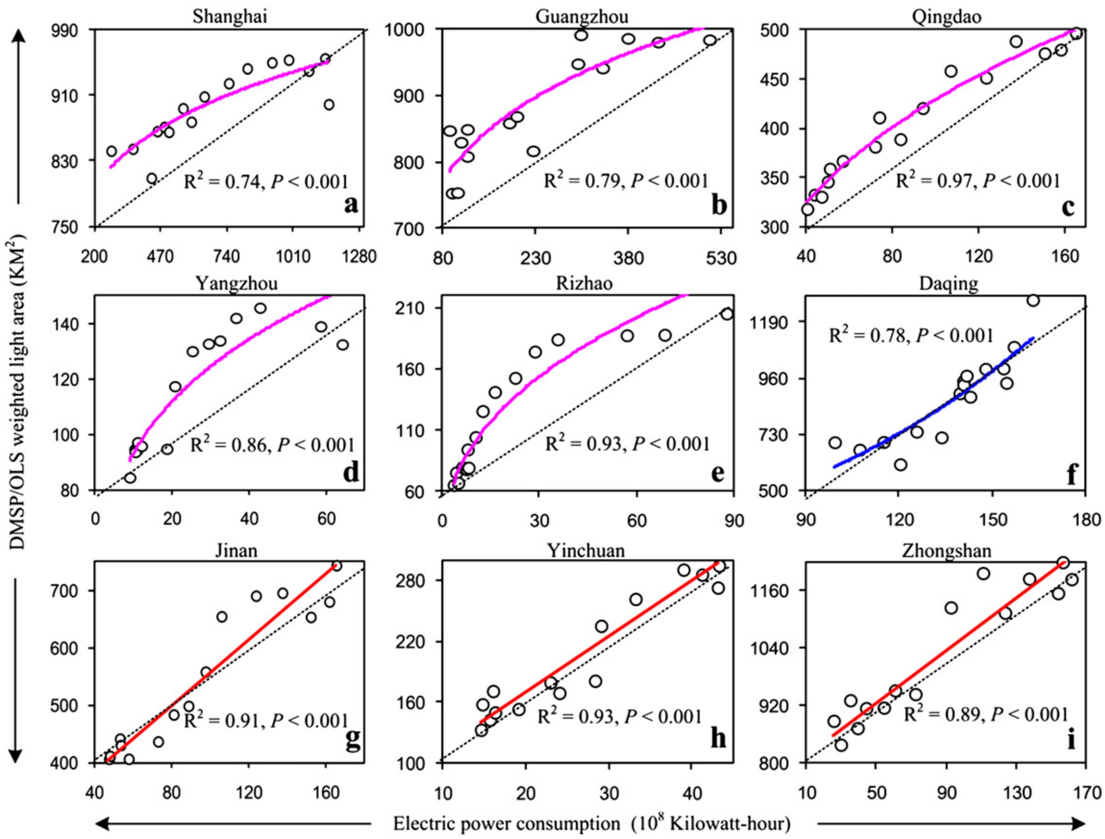

Fig. 9. Diverse responses of DSMP/OLS nighttime light signals to temporal changes in urban electric power consumption from 1994 to 2009 by power-law model (a–e), exponential model (f) and linear model (g–i) for nine China' cities.

lights (Small et al., 2005; 2011). We therefore focused on assessing the linear relationship between the magnitude of nighttime light signals (i.e. weighted light area) instead of lit area and the area of urban land cover (i.e. urban built-up area) over time, in order to examine whether nighttime light signals coordinately and synchronously respond to spatial extensions of urban area. In this study, urban built-up area derived from statistical datasets of cities is defined as the constructed area with well-established infrastructures which is spatially contiguous and has been well developed for non-agricultural use (National Bureau of Statistics of China, 1995–2010).

As listed in Table 1, our results indicate that over 68% of China's cities show a strong positive linear relationship ($R^2>0.5$ and $P>0.05$) between urban built-up area and weighted nighttime light area from 1994 to 2009. This result may imply similar increases in both nighttime light and urban land cover area during urbanization across most of China's cities over the past decades. For individual cities at a local scale, however, the response patterns of nighttime light to increases in urban built-up area could be quietly different over time. As shown in Fig. 8, the growth rate of weighted light area is much smaller than concurrent increase in urban land cover from 1994 to 2009 in both Beijing City (yearly increased by 13.2 km^2 vs. 74.2 km^2, Fig. 8a) and Guangzhou City (yearly 16.4 km^2 vs. 54.7 km^2, Fig. 8b). But in Kaifeng City (yearly 3.2 km^2 vs. 3.5 km^2, Fig. 8c), Kunming City (yearly 10.6 km^2 vs. 11.9 km^2, Fig. 8d), and Chengdu City (yearly 24.0 km^2 vs. 24.6 km^2, Fig. 8e), both urban weighted nighttime light area and urban land cover area show consistent increases during 1994–2009. Moreover, in Nanning City (Fig. 8f), Yinchuan City (Fig. 8g), Zhenjiang City (Fig. 8h) and Guiyang City (Fig. 8i), the rate of increase in nighttime light signals significantly exceed that in concurrent expansion of urban built-up area for the period of 1994–2009, yearly 16.7 km^2 vs. 8.4 km^2, 12.6 km^2 vs. 5.5 km^2, 3.8 km^2 vs. 5.7 km^2 and 17.1 km^2 vs. 4.4 km^2, respectively. In addition, it is quite noticeable that, for a given city with a well-developed rural–urban conversion due to a limited administrative boundary, non-radiometrically corrected signal of nighttime lights within the administrative unit of a city could trend towards saturation, as evidenced in Beijing City and Guangzhou City (shown in Figs. 4 and 8). In this case, radiance-calibrated DMSP/OLS images may be more applicable to assess changes in urban land cover area as represented by Sutton (2003) and Ghosh et al. (2010).

3.6. Estimates for urban electric power consumption

High electric power consumption could be considered as the immediate cause of intense nighttime light brightness in DMSP/OLS imagery (Amaral et al., 2005; Elvidge et al., 2001). Although the exact relationship between electric power consumption for artificial night lighting and satellite-based measures of nighttime light signals remains less understood due to the lack of data, a statistically significant association (with $R^2>0.5$ and $P<0.05$) between urban total electric consumption and nighttime light signals is identified over more than 50% of China's prefectural-level cities (Table 1). Similarly, as discussed above for other urbanization variables, our results reveal that weighted nighttime light area also shows diverse responses to changes in magnitudes of urban electric power consumption over time (Fig. 9), particularly by power law function such as in Shanghai City (Fig. 9a), Guangzhou City (Fig. 9b) and Qingdao City (Fig. 9c), and linear function such as in Jinan City (Fig. 9g), Yinchuan City (Fig. 9h) and Zhongshan City (Fig. 9i).

4. Conclusions

Although DMSP/OLS was not initially designed for observation of human settlements, nighttime lighting brightness involving both stable lights and radiance-calibrated images derived from DMSP/OLS have been extensively used for estimating the spatial expansion of urban development and mapping the spatial distribution of economic activity due to the low-light sensing capabilities of DMSP/OLS at night (Elvidge et al., 1997). Despite the restriction regarding the difference between actual extent of human settlement and nighttime lighted area caused by the effects of over-glow and shrink, DMSP/OLS dataset provides a consistent and timely measure for characterizing urbanization dynamics in terms of spatial expansion, demographic dynamics and economic activity from a regional scale to a global scale (Small et al., 2011).

Our results verified the utility of DMSP/OLS night lights for estimating long-term trends in four urbanization variables: urban population, GDP, built-up area and electric power consumption for most of prefectural-level cities and municipalities in China during 1994–2009. Temporal changes in nighttime light brightness could be statistically significantly associated with demographic and socioeconomic variables in most individual cities through several positive monotonic functions involving linear, power law and exponential models. DMSP/OLS night lights therefore could be indicative of salient urbanization processes in recent China at a local scale. Moreover, our results revealed diverse quantitative responses of DMSP/OLS nighttime stable lights to changes in urbanization variables over time. Various relationships between two time series of weighted nighttime lighting area and statistical measure of urbanization variables could be quantified though linear, power-law and exponential functions. Although observationally-based assessment of nighttime lighting could be used for tracing dynamics in urbanization in terms of spatial, demographic and economic variables, our results suggest that quantitative models should vary for different types of urban development patterns in order to obtain more accurate estimates. In addition, potentially saturated lighting signals for some administrative units with well-developed urban zones (Ghosh et al., 2010) and the widespread effects of over-glow and shrink in DMSP/OLS imagery (Small et al., 2011) may be two challenges for extensive applications of DMSP/OLS data in assessment of local-scale urbanization processes. Therefore, further studies on these problems are needed for extending the utility of DMSP/OLS data in investigation of anthropogenic environment changes.

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