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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.

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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

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