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Urbanization and the thermal environment of Chinese and US-American cities

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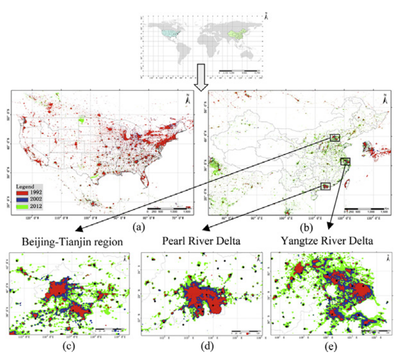
HIGHLIGHTS

- Urbanization modifies light intensities and surface temperatures.
- Light intensities increase with urban area.
- Temperature tendencies indicate decrease at daytime (increasing at nighttime).
- High light intensity regions show less seasonal variability in temperature tendency.

GRAPHICAL ABSTRACT



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ABSTRACT

Urbanization induced change of the thermal environment of cities is analyzed using MODIS LST and DMSP/OLS nighttime light data sets (2001 − 2012) to a) extend previous studies on individual megacities to a city size spectrum; b) investigate the heterogeneous surface thermal environment associated with the urbanization processes in terms of nighttime light intensity and city size; and c) provide insights in predicting how urban ecosystems will respond to urbanization for both a developing and a developed country (China and US-America), and on global scale. The following results are obtained: i) Nighttime light intensities of both countries (and globally) increase with increasing city size. ii) City size dependent annual or seasonal mean temperature tendencies show the urban effect by decreasing daytime and increasing nighttime mean temperatures (particularly in China) while variability can be related to climate fluctuations. iii) Daytime/nighttime seasonal warming tendencies (inferred from regional downscaling within city clusters) show the high light intensity regions to be stable while in low light intensity regions fluctuations prevail.

1. Introduction

The global urbanization process, where human population, material demands of production, human consumption and urban waste discharge expand and become more intense, has recently emerged as a sustainability challenge in an increasingly urbanized world (Alberti

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2005; Johnson 2001; Montgomery 2008; Pataki et al. 2006; Ren 2015). Whereas in 1900 a mere 10% of the global population were urban dwellers, that percentage now exceeds 50% and will rise even more to approach the 80% urbanization level of most industrialized nations today (Grimm et al. 2008). That is, global urban population is projected to increase by 2.7 billion in 2050, nearly doubling today's urban population of 3.4 billion (UN 2010). In addition, urban surface climate is generally characterized by higher surface air temperature, weaker mean wind speed, and lower relative humidity compared with its surrounding suburbs and countryside (Landsberg 1981; Oke 1987).

Although global and regional climate changes are known to have an impact on altering the urban surface climate, the urbanization/anthropogenic induced change in surface parameters, including increased atmospheric greenhouse gas concentration, aerosol emissions, and land use and land cover change, is a major component for the formation and evolution of urban climates (Grimm et al. 2008; Ren 2015; Wu and Yang 2013). Kalnay and Cai (2003) estimated urbanization and other land-use changes accounting for half of the observed reduction in the diurnal temperature range and an increase in mean air temperatures in the United States during the past century. The best-documented example of anthropogenic climate modification is the urban heat island effect (Landsberg 1981; Oke 1987), which affects not only local and regional climate, but also water resources, air quality, human health, and biodiversity and ecosystem functioning (Platt et al. 1994). Thus, research on the effects of global/regional urbanization on urban surface thermal environment may provide insights in predicting how urban ecosystems will respond to urban climate change (Carreiro and Tripler 2005).

Research on global/regional urbanization requires the definition of urban land use, which can be different depending on the questions being addressed (Schneider and Woodcock 2008, see also http://blogs.worldbank.org/sustainablecities/what- does-urban-mean): i) socio-demographic definitions involve administrative boundaries, population size or density, and economic indicators (Utzinger and Keiser 2006); and ii) physical definitions use the presence of human-made structures and materials (Mertes et al. 2015; Taubenböck et al. 2014). Unlike traditional socio-demographic research, employing remote sensing techniques to analyze physical human-made structures and materials in urban surface environment is a relatively recent field of research (Small et al. 2011), and has potential to obtain more comprehensive characteristics relating to urban dynamics and associated environmental consequences during the urbanization processes (Ma et al. 2012).

Nighttime light signals derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) provide striking remotely sensed data to analyze spatiotemporal changes in global urbanization processes (Elvidge et al. 1997; Small and Elvidge 2011; Small et al. 2005; Sutton 2003). Most previous studies have attempted to quantify the correlation between night lighting areas and urbanization variables, including urban expansion (Huang et al. 2016; Zhang et al. 2015), population growth (Ghosh et al. 2010; Sutton et al. 2001; Zhang and Seto 2011), gross domestic product (Doll et al. 2006; Henderson et al. 2012; Sutton and Costanza 2002), and electric power consumption (Amaral et al. 2005). However, to our knowledge, few studies have been concerned with the quantitative relationship among global, regional DMSP/OLS nighttime light signals and remote sensing based urbanization-related surface thermal changes, particularly on a basis of a city size spectrum analysis (details see Section 2).

Unlike using station and simulation data covering socio-demographic areas, remote sensing based technique of physical human-made nighttime light area is used in this study to define urbanization based land use (or city size) and thus to analyze the interrelationship, change tendency and variability of city size, light intensity and urban surface air temperature. It will help enhance our understanding of the spatiotemporal characteristics of urbanization and urban surface thermal environment in global and regional scale. After introducing the remote sensing-based DMSP/OLS nighttime light signals and surface air temperature datasets, methods of analysis are presented (Section 2). Global, country-wide and regional comparison of urban thermal environment and its relation to city size and nighttime light intensity is discussed (Section 3), followed by a concluding summary (Section 4).

2. Data and methods of analysis

Small et al. (2011) indicate that the idea of defining a city as a discrete entity with fixed administrative boundaries may be fundamentally flawed, because human settlement patterns and, more generally, land surface modification can be represented as continuous spatial variation in intensity of development or degree of modification. In this study, spatiotemporal changes of urbanization obtained from global DMSP/OLS nighttime stable lights products (1992, 2002 and 2012, acquired from NOAA National Geophysical Data Center) with the brightness range *DN* of 0 to 63 at the spatial resolution of 30 arc-seconds (~1 km) are used. To reduce the effects of over-glow, usually caused by anthropogenic activities in undeveloped areas that were not taken into account in statistical data of urban development (Elvidge et al. 1997; Small et al. 2005), only spatially contiguous lighted pixel units (subscript 'i') with $DN_i \geq 12$ are discussed below as cities (detailed descriptions of data quality control and threshold choosing see Small et al. (2011)). The area of each pixel within spatially contiguous lighted areas, $a(j)$, is defined as a_i. Thus a city (numbered by 'j') is characterized by its size, $size(j)$. Its light intensity and its light variability are deduced from the spatially contiguous lighted area with brightness $DN_i \geq 12$. Thus, j corresponds to the sequence of spatially contiguous areas exceeding the brightness threshold and i corresponds to the number of pixels in each of these areas. That is

$$City\ size(j) = \sum_i a_i(j)$$

$$Light\ intensity(j) = \left(\sum_i DN_i\right)/size(j) \quad \text{and}$$

$$Light\ variability(j) = std(DN_i)$$

The city size spectrum analysis provided in this study is inspired by the power-law or Zipf's law which implies that small occurrences are extremely common, whereas large instances are extremely rare (Adamic 2000). That holds for huge city samples in a global and subcontinental scale analyses, and it will circumvent limitations of previous studies with their inconsistencies, including differences of time period, regional span and analysis method (see Sections 3.1 to 3.3).

Twelve years of land surface temperature (LST) data of Moderate Resolution Imaging Spectroradiometer (MODIS, MOD11C3) is analyzed provided monthly at 0.05° spatial resolution as a gridded level-3 product for daytime and nighttime to calculate temperature tendencies from 2001 to 2012. To be comparable, the DMSP/OLS nighttime stable light products are resampled according to the spatial resolution of MODIS LST data. Intra-annual seasonality and annual mean temperatures are calculated before a simple linear regression model (against year) is used to obtain the temperature change trend/slope. Inter-annual temperature change tendencies of spring (March to May), summer (June to August), autumn (September to November), winter (December to February) and annual mean of the surface air temperature are evaluated by *F-test* with all significance levels at the *P*-value <0.05 level (unless noted otherwise).

Scale dependent analysis (Section 3) includes a city unit (city size spectrum analysis, see Section 3.1–3.3) and a pixel unit (see Section 3.4). Among, brightness *DN*, daytime and nighttime temperatures and their related tendencies are recorded as pixel units. City size, light intensity, light variability and related city size based averaged temperature tendencies for both daytime and nighttime are calculated in terms of city units. Therefore, besides urbanization and heterogeneous surface thermal environment on individual megacities (Section 3.4), this

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