Science of the Total Environment 605–606 (2017) 426–435

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

The surface urban heat island response to urban expansion: A panel analysis for the conterminous United States

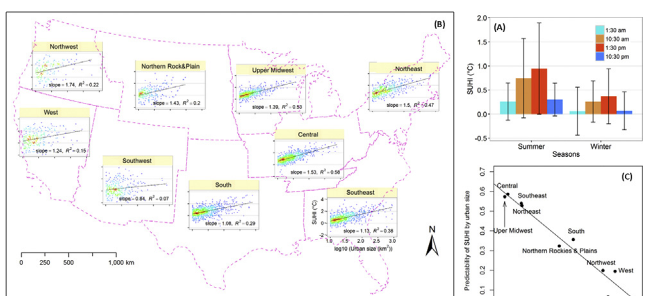
Xiaoma Li [a], Yuyu Zhou [a,*], Ghassem R. Asrar [b], Marc Imhoff [c], Xuecao Li [a]

[a] Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA 50011, USA
[b] Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD 20740, USA
[c] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD 20740, USA

HIGHLIGHTS

- We studied relationship between SUHI and urban area size and their spatial and temporal variation in the conterminous U.S.
- SUHI increases nonlinearly with the increase of urban area size in a log-linear form.
- Doubling urban size increases SUHI as high as 0.7 °C, with larger increase in high latitude areas and in summer and daytime.
- Urban area size explains as much as 87% of SUHI variation, with higher value in regions covered by homogenous land cover.

GRAPHICAL ABSTRACT



A: Temporal (seasonal and diurnal) patterns of surface urban heat island (SUHI) in the US.
B: Spatial variation of summer midday (1:30 pm) SUHI and urban size relationship.
C: Relationship between land cover heterogeneity and predictability of SUHI by urban size.

ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 25 June 2017
Accepted 26 June 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Urbanization
Land surface temperature
Urban expansion
Spatiotemporal variation
Urban area

ABSTRACT

Urban heat island (UHI), the phenomenon that urban areas experience higher temperatures compared to their surrounding rural areas, has significant socioeconomic and environmental impacts. With current and anticipated rapid urbanization, improved understanding of the response of UHI to urbanization is important for developing effective adaptation measures and mitigation strategies. Current studies mainly focus on a single or a few big cities and knowledge on the response of UHI to urbanization for large areas is limited. As a major indicator of urbanization, urban area size lends itself well for representation in prognostic models. However, we have little knowledge on how UHI responds to urban area size increase and its spatial and temporal variation over large areas. In this study, we investigated the relationship between surface UHI (SUHI) and urban area size in the climate and ecological context, and its spatial and temporal variations, based on a panel analysis of about 5000 urban areas of 10 km^2 or larger, in the conterminous U.S. We found statistically significant positive relationship between SUHI and urban area size, and doubling the urban area size led to a SUHI increase as high as 0.7 °C. The response of SUHI to the increase of urban area size shows spatial and temporal variations, with stronger SUHI increase in Northern U.S., and during daytime and summer. Urban area size alone can explain as much as 87% of the variance of SUHI among cities studied, but with large spatial and temporal variations. Urban area size shows higher association with SUHI in regions where the thermal characteristics of land cover surrounding the urban area are more homogeneous, such as in Eastern U.S., and in the summer months. This study provides a practical approach for large-scale assessment and modeling of the impact of urbanization on SUHI, both spatially and temporally.

* Corresponding author.
E-mail address: yuyuzhou@iastate.edu (Y. Zhou).

http://dx.doi.org/10.1016/j.scitotenv.2017.06.229
0048-9697/

1. Introduction

Urban heat island (UHI) formation, or the phenomenon that urban areas experience higher temperatures compared to their surrounding rural areas, is observed worldwide for cities across a broad range of sizes and locations (Clinton and Gong, 2013; Heinl et al., 2015; McCarthy et al., 2010; Oke, 1973; Peng et al., 2011; Santamouris, 2015; Wienert and Kuttler, 2005; Zhao et al., 2014). The UHI is attracting increasing attention from policy decision makers, investors, health authorities, energy and transportation planners, and the scientific community because of its significant adverse impacts on the health of urban dwellers (especially those at risks such as children and elderly) (Dousset et al., 2011; Lemonsu et al., 2013), increased energy demand for cooling (Lowe, 2016; Sun and Augenbroe, 2014), and alteration of vegetation phenology (Li et al., 2016; Zipper et al., 2016). Increasing population and greater migration from rural to urban areas due to socioeconomic development will result in large scale urban expansion (Seto et al., 2012). As a result, there is a high probability that in future people will live in ever warmer cities, where the UHI is exacerbated by anticipated warmer climate (Jones et al., 2015; Lemonsu et al., 2013; Santamouris, 2014). To design effective adaptation measures and mitigation strategies, there is a need for improved information and knowledge about the extent and magnitude of UHIs caused by the expected rapid urbanization, especially in developing regions such as Southeast Asia and Africa (Cao et al., 2016; Kolokotroni et al., 2012; Long et al., 2016; Masson et al., 2013; Masson et al., 2014). For example, it is essential to estimate energy use caused by UHI in the context of rapid urbanization for future infrastructure planning and development in major urban systems (Santamouris, 2014; Santamouris et al., 2015). Understanding how UHI respond to urbanization is an essential first step for these applications.

Two types of indicators, air UHI (AUHI) and surface UHI (SUHI), were widely used to study UHI. AUHI is based on air temperature, which is measured using thermometer installed at field sites or mounted on vehicles (Jason and Christopher, 2015; Oke, 1973; Pichierri et al., 2012; Schatz and Kucharik, 2014; Smoliak et al., 2015; Wang et al., 2017; Zhang et al., 2014). SUHI is based on land surface temperature (LST), which is measured by radiometers on board aircraft or satellites (Li et al., 2013a, b; Li et al., 2012; Voogt and Oke, 2003; Zhou et al., 2014a). AUHI has advantage in characterizing fine spatial and temporal variations of UHI, and is suitable for studying impacts of local indicators of urbanization (e.g., sky view factor, floor area ratio) and climate factors (e.g., wind, cloud) contributing to SUHI (Morris et al., 2001; Oke, 1973; Schatz and Kucharik, 2014; Zhao et al., 2011). The major advantage of SUHI is that it can be calculated easily for a large number of cities across large spatial domains. This allows comparing UHI among cities in large regions to explore the role of urbanization in influencing SUHI (Clinton and Gong, 2013; Cui et al., 2016; Heinl et al., 2015; Imhoff et al., 2010; Peng et al., 2011; Zhang et al., 2012; Zhao et al., 2014; Zhou et al., 2014d). Therefore, we focused on using SUHI in this study.

Response of SUHI to urbanization has been widely studied for a single or a few select large cities using indicators such as impervious surface area, population density, and building density (Jason and Christopher, 2015; Li et al., 2011; Oke et al., 1991; Oke, 1982; Xiao et al., 2008; Zhao et al., 2011; Zhou et al., 2014a). Using these indicators, numerical (Cao et al., 2016; Wang et al., 2016) and statistical (Deilami and Kamruzzaman, 2017; Su et al., 2012) models have been developed to simulate SUHI under urbanization (e.g., urban expansion). However, these models are not applicable for large areas that encompass multiple metropolitans because: 1) the required variables and associated datasets (e.g., impervious surface area) are usually not available, 2) the computing cost increases significantly with the growth of study area (Lauwaet et al., 2015). As UHI dataset for large areas is increasingly needed for impact analysis and developing effective adaptation measures and mitigation strategies, new methods or surrogate variables are needed to address these limitations for modeling SUHI with different urbanization scenarios over large areas.

Three types of urbanization indicators (i.e., population, economy, and area) are usually used to study how SUHI/UHI responds to urbanization over large areas (Cui et al., 2016). Many early studies used population as a primary indicator. For example, Oke (1973) reported a relationship between AUHI and population size for St. Lawrence Lowland region of Canada, in North American, and in Europe cities. Hung et al. (2006) focused on the relationship between SUHI and population size in 18 Asian mega-cities. Recent studies used urban area size because of its global accessibility from satellite observations and urban growth models for each city. For example, Imhoff et al. (2010), Tan and Li (2015), and Du et al. (2016) studied the correlation between SUHI and urban area size in Northeastern U.S., in Hebei plain of China, and in Yangtze River Delta, respectively. Similar studies were also performed at the national level (e.g., China by Zhou et al. (2014d)) and globally (e.g., by Peng et al. (2011), Clinton and Gong (2013), and Cui et al. (2016)).

Previous studies showed that the relationship between SUHI and impervious surface area varied in space (Imhoff et al., 2010) and time (Buyantuyev and Wu, 2010). Accordingly, the response of SUHI to urban expansion may also have strong spatiotemporal variations but is less studied. Current studies on the response of SUHI to urban expansion for large areas are mostly performed for specific regions, for example in Hebei Plain of China (Tan and Li, 2015) and in Northeastern U.S. (Imhoff et al., 2010), except for a global study by Cui et al. (2016). This is mostly because the response of SUHI to urban expansion varies in climate background, land cover, and economic development stage and the response may become weaker with increasing study area (Cui et al., 2016; Peng et al., 2011). In addition, the temporal variation of response of SUHI to urban expansion is also not systematically studied as current studies mostly focused on one or a few time periods, e.g., annual (Cui et al., 2016), summer (Tan and Li, 2015), and daytime (Zhou et al., 2013), except for Du et al. (2016) who investigated the relationship between urban area size and SUHI of both daytime and nighttime for four seasons in the Yangtze River Delta of China. To better understand the impacts of urbanization on SUHI, improved understanding of the spatial and temporal variation of the response of SUHI to urban expansion is highly needed.

The objective of this study is to investigate the relationship between SUHI and urban area size and how it changes spatially and temporally in the conterminous U.S. We quantified daytime and nighttime SUHI for summer and winter seasons for about 5000 urban areas, to understand how SUHI responds to the change of urban area size. Specifically, we attempted to answer two questions: (1) How does SUHI respond to urban expansion, namely the increase of urban area size? (2) What are the spatial and temporal variations of the response of SUHI to urban expansion? The answer to these questions and scientific knowledge gained are useful for quantitatively assessing and modeling the impact of urbanization on SUHI, both spatially and temporally, and for developing mitigation/adaptation measures, especially in anticipated warmer climate conditions for the rest of this century. The following sections describe the data and method used (Sections 2), results and discussion (Section 3), and concluding remarks (Section 4).

2. Data and methodology

We used the LST product retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard NASA's Terra and Aqua satellites to quantify SUHI. MODIS LST has several unique attributes as compared with other remotely sensed thermal infrared data (e.g., Landsat, Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager (MSG-SEVIRI)): 1) large spatial coverage, 2) decent spatial resolution (1 km), (3) high temporal resolution (four overpasses per day at approximate 1:30 am and 1:30 pm, and 10:30 am and 10:30 pm, local time), and (4) more than ten years of data. It has been