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Remote sensing applications in monitoring urban growth impacts on in-and-out door thermal conditions: A review

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ABSTRACT

Urban growth and the consequent expansion of impervious surfaces influence a landscape's thermal characteristics by raising Land Surface Temperatures (LST). Resultant warming may cause among others, thermal discomfort, high prevalence of heat related health conditions, air pollution, increased water usage and energy demand for air-conditioning. Recently, studies aimed at understanding the impacts of urbanization and subsequent landscape transformation on in-and-out door temperature have increased significantly. This review therefore provides synthesis on the progress of space-borne remote sensing in monitoring the implications of urban growth on thermal characteristics. It was observed that despite the relative coarse spatial properties; medium resolution sensors (i.e. Landsat and MODIS) have become valuable in characterizing urban thermal conditions, especially in data-limited areas. More importantly, literature shows that thermal assessments have been confined to examination of historical and current conditions, without considering current research studies. This work identifies low temporal resolution that characterizes the commonly used medium spatial resolution thermal sensors as a major limitation to mapping urban surface temperature. There is therefore need for future studies to shift towards integrating new crop of high resolution satellite data with existing high temporal and low spatial resolution sensors. Such techniques can lead to the development of robust spatial datasets suitable for improved seasonal and long term monitoring of urban thermal patterns.

1. Introduction

Studies have shown that the spatial extent and population of urban areas are increasing globally, and the growth is expected to continue beyond the year 2100 (De-Simone et al., 2011; Blake et al., 2011; Seto et al., 2012). By the year 2008 for instance, more than 50% of the world's population was already living in cities and their immediate surroundings (De-Simone et al., 2011). Urban population is projected to increase by a further 10% by 2030, reaching 70% in 2050 (Blake et al., 2011; Anon, 2007, 2014). According to Seto et al. (2012), urban areas are expanding twice faster than population growth and are a major driver of environmental change. For instance, due to the characteristic conversion of natural landscapes to impervious surfaces, urbanization has been linked to an increase in size and intensity of the Urban Heat Island (UHI), which is associated with an increase in water and energy demand, high levels of air pollution and increased heat related health risk (Valsson and Bharat, 2009; Blake et al., 2011; Zhang et al., 2013; Guhathakurta and Gober, 2007; Saitoh et al., 1996; Tran et al., 2006). Other impacts include depletion of freshwater resources, uncomfortable sleeping nights, increase in heat related mortality and habitat loss (Seto et al., 2012; Luber and McGeehin, 2008; McDonald et al., 2011; Kusaka et al., 2012). Furthermore, elevated temperatures increase the exposure of the society vulnerable, due to their low coping strategies and mechanisms (Newland, 2011). Monitoring and forecasting urban growth patterns and their implication on urban thermal characteristics is therefore valuable for planning and optimization of physical landscapes and socio-economic services (Bhattacharjee and Ghosh (2015).

Recently, the use of remotely sensed data has emerged as a reliable approach for assessing urban landscape transformation and its implication on urban climate. Remotely sensed data offers better prospects in providing up to date spatial and temporal data necessary for understanding the complex relationship between urban growth and in-

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and-out door thermal conditions. Recent studies that evaluated the utility of remotely sensed data in urban climate studies have shown great promise (Acharya et al., 2015; Cai et al., 2011; Franco et al., 2015; Zhou and Wang, 2011; Amiri et al., 2009). Zhou and Wang (2011) for instance assessed the dynamics of LST in response to land cover change in rapidly urbanizing city of Kunming, China, while Zhang et al. (2009) investigated bi-temporal characterization of LST in relation to impervious surface area, Normalised Difference Vegetation Index (NDVI) and Normalised Difference Built Index (NDBI) using sub-pixel image analysis. They managed to map urban growth, using both qualitative (general Land Use and Land Cover [LULC] classes) and quantitaive measures (indices). The changes in vegetation spatial structure and impervious areas were, therefore, monitored using change detection methods. This indicated that there is a wide variety of remote sensing approaches that can be used to depict LULC changes. The growth patterns observed in these studies managed to explain changes in surface temperature. Also, Amiri et al. (2009) analyzed the spatial and temporal dynamics of LST in relation to fractional vegetation cover and land cover in Tabriz, Iran. In their quantitative approach, they found out that LST was high in areas where vegetation fractional cover was low. Recently Lin et al. (2016) focused on winter in-door thermal and heating demand of urban residential buildings in China during the hot and cold seasons in relation to LST changes. that the study showed that warming, due to urban growth and land surface alteration, increased energy demand for in-door cooling in the hot season. Other studies on the implication of urbanization on urban thermal properties include Voogt and Oke (2003), Rizwan et al. (2008) and Goshayeshi et al. (2013). The aforementioned studies revealed that urban land cover dynamics modify urban thermal conditions, by elevating surface temperatures at an alarming rate. In this regard, there is need to assess these impacts on a city's specific local temperatures to ensure sustainable growth and adoption of relevant mitigation measures.

Previous studies that adopted remotely sensed data indicated that the spatial structure of impervious surfaces, wetlands and vegetation has a direct influence on LST (Connors et al., 2013; Hasanlou and Mostofi, 2015; Keramitsoglou et al., 2011). Green areas and water bodies have low temperatures and act as cool islands during the day and also alleviate heat by fragmenting the urban thermal island and vice-versa (Rasul et al., 2015; Zhang et al., 2012). Conversely, built up areas absorb high amounts of heat and are regarded as a major source of heat in urban zones (Sithole and Odindi, 2015). Studies have also revealed that the net effect of buildings and vegetation in an area depends on their density (Odindi et al., 2015; Jalan and Sharma, 2014; Hu and Jia, 2010). For example, in a study conducted in South Africa, Odindi et al. (2015) observed that moderately built “leafy” suburbs were slightly cooler than areas with sparse vegetation, while temperature increased with building density. This is also confirmed by the study by Jalan and Sharma (2014) who observed that expansion of built-up areas at the expense of green-spaces resulted in warming of the city of Jaipur in India by an average of 2.99 °C. A number of studies (Jenerette et al., 2007; Collatz et al., 2000; Ganopolski et al., 1998) have demonstrated this inverse influence of vegetation on LST. These studies indicated that, within a city, areas with high vegetation cover proportion experience high extent of cooling by evaporation, resulting in low surface temperatures.

Review papers on urban surface temperature have mostly focused on spatial and temporal LST variations and heat island retrieval, using remote sensing (Mohamed et al., 2016; Sattari and Hashim, 2014; Voogt and Oke, 2003; Weng et al., 2004). For example, Mohamed et al. (2016) recently reviewed methods of LST and emissivity retrieval, using low and medium spatial resolution satellite data. However, previous reviews did not highlight on methods to quantify and link the long term changes in urban thermal characteristics to urban growth and socio-economic impacts. On the other hand, reviews on the implications of temperature on in-and-out door thermal comfort assessment have looked at models of thermal comfort analysis, as well as implications on energy consumptions (Goshayeshi et al., 2013; Kwong et al., 2014; Charles, 2003; Garcia-Frapolli et al., 2007). However, the reviews did not include the methods on incorporation of remote sensing thermal data in estimating thermal comfort and impacts on energy consumption. For example, previous studies have quantified thermal comfort and energy consumption, using indices, such as Thom's Discomfort Index and Degree Days, respectively, which use in situ air temperature measurements., There is therefore a need to identify robust remote sensing based approaches that can potentially quantify thermal comfort and energy consumption. To the best of our knowledge, no review to date has focused on approaches for predicting future LST and urban heat island patterns, using remotely sensing land use and land cover trends. In order for sustainable development to be achieved, it is necessary to consider future implications, by embracing predictive techniques that can link these changes with potential impacts.

Based on the aforementioned shortcomings, this paper therefore seeks to review the progress in remote sensing applications in monitoring the impacts of urban growth on in-and-out door thermal conditions. Firstly, the study provides a brief overview of the general implications of urban growth on in-and-outdoor thermal conditions, highlighting the contribution of impervious surfaces, buildings and urban vegetation on spatial temporal LSTs. Secondly, the study explores the utility of remotely sensed data in assessing the impacts of urban growth on in-and-outdoor thermal conditions, as well as examines available analytical algorithms for assessing urban growth and its influence on urban thermal conditions. Also, included in this review are remote sensing based prediction methods for future LST distribution, which can also be used for estimating the impact of urbanization on outdoor thermal discomfort. Finally, the review discusses the impact of urban growth on air-conditioning energy demand, as well as possible future directions in the applications of remotely sensed data in assessing and monitoring the impacts of urban growth on in-and-out door thermal conditions.

2. Implications of urban growth on in-and-outdoor thermal conditions

Urbanization is characterized by surface alterations, which mostly entails an increase in area covered by surfaces tha absorb large amounts of heat (Sobrino et al., 2012; Amiri et al., 2009; Zhang et al., 2009). For example, vegetated areas are replaced with impervious surfaces and buildings, resulting in elevated surface temperatures much higher than the surrounding rural and undisturbed areas (Johnson et al., 2014; Steeneveld et al., 2014; Tomlinson et al., 2011; Hua et al., 2013; Song and Wu, 2015; Sobrino et al., 2012). For example, an increase in built-up area alters the energy balance by increasing heat absorption and heat transfer between the earth's surface and the lower atmosphere (Guan, 2011). According to Xian and Crane (2005), urbanization alters air temperature of the atmospheric boundary layer, making it a key component of the surface energy balance. Generally, the impact of elevated temperatures within cities varies spatially, as a consequence of differences in physical exposure, landscape characteristics and socio-demographic factors (Johnson et al., 2014). Spatial variation in land cover distribution influences distribution of heat absorption rates and hence physical exposure patterns to extreme heat. Moreover, literature has revealed that the increase in surface temperatures have the potential to expose residents to heat related stress, especially the urban poor without air conditioning facilities (Parsons, 2014; Hsiang, 2010; Dokladny et al., 2006).

3. Remote sensing urban growth impacts on in-and-outdoor thermal conditions

Traditionally, in-situ meteorological observations have been used in near-surface (usually 2 m above the ground) temperature analysis. These measurements were used to explain temporal patterns and