



## Research article

## Attenuating the surface Urban Heat Island within the Local Thermal Zones through land surface modification

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## ABSTRACT

Inefficient mitigation of excessive heat is attributed to the discrepancy between the scope of climate research and conventional planning practice. This study approaches this problem at both domains. Generally, the study, on one hand, claims that the climate research of the temperature phenomenon should be at local scale, where implementation of planning and design strategies can be more feasible. On the other hand, the study suggests that the land surface factors should be organized into zones or patches, which conforms to the urban planning and design manner. Thus in each zone, the land surface composition of those excessively hot places can be compared to the zonal standard. The comparison gives guidance to the modification of the land surface factors at the target places.

Specifically, this study concerns the Land Surface Temperature (LST) in Wuhan, China. The land surface is classified into Local Thermal Zones (LTZ). The specifications of temperature sensitive land surface factors are relative homogeneous in each zone and so is the variation of the LST. By extending the city scale analysis of Urban Heat Island into local scale, the Local Surface Urban Heat Islands (LSUHIs) are extracted. Those places in each zone that constantly maintain as LSUHI and exceed the homogenous LST variation are considered as target places or hotspots with higher mitigation or adaptation priority. The operation is equivalent to attenuate the abnormal LST variation in each zone. The framework is practical in the form of prioritization and zoning, and mitigation strategies are essentially operated locally.

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## 1. Introduction

## 1.1. Excessive heat in urban areas and inefficiency of mitigation efforts

The warming rate of the urban areas is constantly higher than that of the globe (Jenerette et al., 2011; Oke, 1982; Stone, 2007). The excessive heat in urban areas is expected to be exacerbated through the continuous interaction between local and global climate process (Jenerette et al., 2011; Oke, 1973; Wilby, 2008). To characterize such phenomenon, the temperature difference between the urban areas and rural surroundings is measured by the magnitude of the Urban Heat Island (UHI) (Arnfield, 2003; Oke, 1982), which has been examined for nearly 200 years since 1800s (Howard, 1833). The understanding of the UHI has continuously been improved by

partitioning it into Urban Boundary Layer (UBL) and Urban Canopy Layer (UCL) UHIs, and subsequently UHI of the air temperature and surface UHI (SUHI) of the land surface temperature (LST) within the UCL (Oke, 1976; Voogt and Oke, 2003). Among them, the SUHI becomes one of the major concerns as the LST governs the near surface energy balance, modifies the surface biochemical processes, and thus influences the microclimate in urban areas (Jenerette et al., 2011).

Despite of the long history of the UHI investigation, the negative socioecological impacts of the UHI, unfortunately, have only been realized lately (Baccini et al., 2008; Grimmond et al., 2010; Michelozzi et al., 2009). The impacts can be fatal to human lives as demonstrated that human mortality rate can be 4% higher during heat waves (Jones et al., 2015; Larsen, 2015; Perera, 2012). This is highlighted by a number of studies on the consequences of extreme heat. For instance, while over 70,000 people in Europe were killed by an extreme heat event (EHE) in 2003 (Robine et al., 2008; Stone et al., 2012; Valleron and Boumendil, 2004), Arizona led the death number due to heat exposure for 10 years from 1993 to 2002 (Control and Prevention, 2005). The impacts also threatens non-

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human lives such as vegetation and biological processes, where it lowers tree vitality, increase vegetation pest, and modifies soil drying and biological regulation (Jenerette et al., 2009; Katul et al., 2003; Roloff et al., 2009).

In order to mitigate the rising temperature citywide from the municipal perspective, the site level mitigation and adaptation efforts should extend towards land-use planning for neighborhoods and communities (Larsen, 2015). Such inclusiveness and coverage inevitably lead to uncertainties either in risk identification or strategy decision and require the tools such as the vulnerability mapping to be strongly local oriented when identifying the risks (Larsen, 2015; Norton et al., 2015). However, the UHI defined through conventional “urban-rural” dichotomy treats the entire city uniformly and restricts local scale investigations. Further identification of risks, vulnerability and mitigations strategies are thus eliminated by lacking proper descriptors at local scale. For example, recent vulnerability maps such as those of Detroit and Phoenix, U.S., and Port Phillip, Melbourne, Australia that directly apply temperature maps oversimplified the analysis at city scale. Places identified with higher temperature are essentially compared at city scale of the entire study area, thus local abnormal temperature variations are underestimated. In addition, these studies also ignore the uncertainties of data noise and temporal variations (Patt et al., 2005; Preston et al., 2011). Meanwhile, mitigation strategies tend to inefficiently respond to the problem of higher temperature in urban areas. Despite the explicit assertion of the Intergovernmental Panel on Climate Change that rising temperature may be due to persistent anthropogenic land surface modification (Griggs and Noguer, 2002), some cities improperly take the greenhouse gas emission control as the primary concern (Stone et al., 2012). Other cities hesitate in implementing different strategies. For instance, increasing vegetation cover may lead to substantial temperature decrease in one place (Gill et al., 2007), whereas higher surface albedo could bring better cooling effect in another (Georgescu et al., 2014). Such hesitation is attributed to the land surface diversity and the variations of the interactions between local land surface factors and climate process.

### 1.2. Characterizing the diversity of the urban thermal environment

One attempt to capture the variation of temperature within urban areas is the initiation of the Local Climate Zone (LCZ) scheme (Stewart and Oke, 2009, 2012; Stewart, 2011a). While the “urban-rural” dichotomy oversimplifies the spatial heterogeneity of the LST (Stewart, 2011a, 2011b), the LCZ was proposed to characterize such diversity by classifying the urban areas into zones with homogeneous LST behaviors based upon climate sensitive indicators extracted from land surface factors instead of aiming at the climatic phenomenon. The land surface oriented classification relies on the premise that the variations of the indicators such as Sky View Factor (SVF) (Chudnovsky et al., 2004; Giannopoulou et al., 2010; Unger, 2004), building surface fraction (Weng and Lu, 2008; Weng et al., 2006) and Impervious Surface Fraction (ISF) (Song et al., 2014; Yuan and Bauer, 2007) governs the LST regulations. Focusing on land surface, the LCZ scheme guarantees its applicability in urban planning and design domain even though the LCZ was initiated for locating weather stations to capture heterogeneous of urban climate processes. For example, a modified version of LCZ to the city for climate mapping and planning has already been applied in Szeged, Hungary (Lelovics et al., 2014; Unger et al., 2014). More progressively, the LCZ has been proved to be an effective standard for integrating local climate information into urban planning and design practice (Middel et al., 2014). Thus the LCZ scheme serves to the planning and design at 2 levels, where it characterizes the heterogeneous land surface-climate interactions

at local scale and can be helpful in selecting relevant strategies locally, and it standardizes the land surface factors into zones both abnormal temperature behavior and mitigation strategies can be referenced. Ultimately, the prioritization and zoning fit into the planning and design convention.

### 1.3. Attenuating the surface Urban Heat Island at local scale

Building upon the studies mentioned in Section 1.3, this study intends to exhibit the strength of LCZ scheme of mapping the excessive heat mitigation procedure to local level and thus the procedure can fit into conventional planning and design with practical and stepwise manner. Throughout the process, one may notice that the LCZ scheme is flexible enough and can be modified to only consider the surface thermal behavior. The modified version of the LCZ in this study aims at the LST and is referred as the Local Thermal Zone (LTZ), within which the study proposes an explicit two-step procedure to prioritize extreme heat mitigation, namely risk ranking and strategy recommendation. Technically, first, by leveraging the concept of the UHI, the study proposes the Local Scale UHI (LSUHI) as measurable local temperature bumps to describe and locate the locally higher LST in the LTZs. Thus not only places with globally higher LST would be considered, but also those with locally higher LST. Second, based upon the premise that the LST discrepancy is triggered by the land surface specification difference, the potential mitigation strategy can be derived by comparing the land surface indicators of the LSUHI and its corresponding LTZ standards given that the indicators are temperature sensitive. While such comparison and mitigation are ultimately at local level within the LTZ, the mitigation becomes attenuation hierarchically.

## 2. Study area

The city of Wuhan, located in central China, is selected for case study. The study area with a spatial extent of  $46 \times 36$  km covers the entire downtown Wuhan and its rural surroundings. It is bounded by the NW and SE coordinates of  $30^{\circ}43'53''N$ ,  $114^{\circ}4'49''E$  and  $30^{\circ}24'0''N$ ,  $114^{\circ}32'34''E$ , respectively (Fig. 1). This coverage is sufficient to exhibit the heterogeneous land surface composition of the city as the water bodies are highlighted in blue by the false color combination in Fig. 1 and scattered across the city, and the vegetation is highlighted in green and mainly distributed around the built-up areas of the city (Wang et al., 2016).

Wuhan is known for its hot weather with nearly 40 days of diurnal temperature over  $35^{\circ}C$  and 30 days of nocturnal temperature over  $28^{\circ}C$  annually. As the fifth largest city of China and the home of over 8-million dwellers, Wuhan imperatively demands investigation of its thermal environment.

## 3. Methodology

The research starts with segmenting the study area into LTZs, where each LTZ possesses homogeneous LST variations. The LSUHI is then identified as the place with excessive heat compared to the homogeneous LST variation in each LTZ (Fig. 2(a)). To make the risk ranking more robust against temporal uncertainties, the temporal behavior of the LSUHI is also considered and those places with higher frequency of being the LSUHIs are referred as hotspots to prioritize the attenuation strategies at local scale as mentioned in Section 1.3, thus the 2-step attenuation is explicitly problem oriented. In addition to the heat problem, improving human well-being means that socio-economic factors should be encompassed in the ranking (Wu, 2013). However, only population and land use information is available for this research.

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