Urban Forestry & Urban Greening 27 (2017) 109–116

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

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

# Spatial and temporal variability of air temperature across urban neighborhoods with varying amounts of tree canopy

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ARTICLE INFO

*Keywords:*
Climate
Green infrastructure
Green space
Heat island
Microclimate
Tree
Urban

ABSTRACT

Recent studies have emphasized the presence of microclimates in urban settings, but most do not have the high resolution observations necessary to understand the interactions taking place at a neighborhood scale. This study used a network of 10 identical weather stations and high resolution land cover data in Knoxville, Tennessee, to analyze the microclimates of a medium-sized city with a temperate climate. Two stations were installed in each of four urban neighborhoods in locations with varying localized tree cover, and two additional stations were installed in the center of downtown and in a nearby urban nature center. The intra-neighborhood results suggested that there is significant temperature variability within a single neighborhood based on the tree canopy density immediately surrounding a given weather station. However, the inter-neighborhood variability (differences between neighborhoods) was similar in magnitude, which suggests that the overall differences in neighborhood characteristics also have an effect on climate. Land cover at the neighborhood scale (in particular tree canopy percentages at the 500-m radii) had the highest correlation with the minimum daily temperature (Tmin) during the summer season. Maximum daily temperature (Tmax) relied most on the distance of each station from Downtown and the amount of impervious area in the 50 m surrounding each station. Tmax was also most influenced by surrounding land cover during dry conditions (a Dry Moderate air mass). Overall, highly localized impervious land cover percentages and larger-scale forested canopy were important in explaining temperature fluctuation, pointing to the importance of scale in microclimate assessments. Dry air masses enhanced the relationship between land cover and temperature during the day, while moist air masses did the same overnight. These data can be used to better inform planning strategies to build resiliency to extreme heat into urban environments by considering the influence of tree canopy.

## 1. Introduction/background

Between 1950 and 2014, the percentage of the world's population classified as urban dwelling increased from 30% to 54% (UN, 2014). Urbanization has many documented adverse effects, including an increase in energy consumption, the deterioration of living environment (Konopacki and Akbari, 2002), an increase in ozone levels (Rosenfeld et al., 1998), and warmer urban streams (Somers et al., 2013; Nelson and Palmer, 2007; Hathaway et al., 2016). Further, More extreme heat waves are likely in city centers and are expected to increase due to climate change (Gao et al., 2012; Luber and McGeehin, 2008), under which extreme heat events are anticipated to become more recurrent and longer lasting in the next century (Meehl and Tebaldi, 2004). Thus, determining how to live in urban environments in a sustainable manner that promotes public and ecological health is critical.

A well-documented phenomenon that occurs due to urbanization is the urban heat island (UHI) (Oke, 1982). This effect is characterized by warmer daytime and nighttime temperatures in a city compared to its surrounding areas. It is more pronounced in larger cities with dense urban development and sparse vegetation (Mallick and Rahman, 2012). The greatest difference in temperature typically takes place overnight, with the urban area producing a higher daily minimum temperature (Tmin) and therefore a lower diurnal temperature range (DTR) (Oke, 1982; Arnfield, 2003), that is, the difference between the daily maximum temperature (Tmax) and Tmin). Higher Tmax is primarily caused by the low albedo (Taha, 1997; Giridharan et al., 2004), or low reflected light, and a lack of vegetation, which leads to lower evapotranspiration rates (Taha, 1997; Shukla and Mintz, 1982; Grimmond and Oke, 1999).

The study of urban microclimates and their relationship to land

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http://dx.doi.org/10.1016/j.ufug.2017.07.001
Received 11 April 2017; Received in revised form 1 July 2017; Accepted 4 July 2017
Available online 08 July 2017

cover and population characteristics has become more prevalent over the past ten to fifteen years (Stabler et al., 2005; Harlan et al., 2006; Hart and Sailor, 2009; Ellis et al., 2017). Studies have analyzed the correlation between the UHI and other characteristics of an urban environment, including: vegetation (Linden, 2011), population density and night light (Linden et al., 2015), percentage of impermeable surfaces (Linden et al., 2015; Hass et al., 2016), the spatial pattern of greenspace (Li et al., 2013; Connors et al., 2013), and various land use/land cover features (Hart and Sailor, 2009). Since tree canopy cover (Hart and Sailor, 2009) and built/paved surface coverage (Connors et al., 2013; Linden et al., 2015) have shown the greatest effect on temperature variation, these two land cover characteristics, in addition to the distance of an area from the city center, are chosen herein for further analysis.

Within the context of vegetative contributions to temperature mitigation, planting and/or protecting existing vegetation, which adds shade and evapotransporative cooling, is a promising technique being considered to reduce urban heat and falls within the increasingly promoted use of green infrastructure in urban environments. Studies have shown that urban parks (i.e., singular, large green spaces) have a cooling effect on surrounding areas (Chang et al., 2006; Doick et al., 2014; Ca et al., 1998). However, the effectiveness of parks may also vary by individual park characteristics (Chang et al., 2006). Thus, the interactions between vegetation and surrounding land uses, the density of green space, and other factors may produce a patchwork of climates, or microclimates, within an urban setting (Stabler et al., 2005). There is a critical need to understand these interactions to develop mitigation strategies and support sustainable development using strategically placed green infrastructure.

These smaller-scale analyses require higher-resolution climate data. Methodologies used to obtain a higher spatial density of temperature data include remote sensing (Li et al., 2013; Connors et al., 2013; Voogt and Oke, 2003), observational transects by car (Yokobori and Ohta, 2009; Hart and Sailor, 2009), or a collection of surface observation networks (multiple weather stations) (Holmer et al., 2013; Linden et al., 2015). Although many studies have investigated urban microclimates using satellite derived land surface temperatures (i.e. remote sensing), a recent study by Ho et al. (2016) suggests these may be a poor proxy for near surface air temperatures, making studies based on surface observations of great importance. Temporally, data are collected on select clear, warm days during the summer (Hart and Sailor, 2009; Ca et al., 1998), over the course of several months (Doick et al., 2014; Ca et al., 1998), or long-term (Linden et al., 2015; Gallo et al., 1996; Li and Roth, 2009). The use of higher-resolution land cover data is also necessary to thoroughly understand the interaction between land use/land cover and temperature. The National Land Cover Database (NLCD) provides free, easily accessible land cover information, and is used in many fields of study (Theobald et al., 2009; Heisler et al., 2007). However, this 30-m resolution data may limit smaller-scale studies (Nowak and Greenfield, 2010) by underestimating tree canopy and impervious cover percentages. Limitations of previous studies on the UHI include low spatial coverage of temperature data (Hart and Sailor, 2009; Yokobori and Ohta, 2009; Linden, 2011), limited temporal coverage of temperature data (Ca et al., 1998; Hart and Sailor, 2009; Stewart and Oke, 2010), or the use of low-resolution land cover data (Stabler et al., 2005; Heisler et al., 2007). Further, minimal study has been performed on the UHI in the warm, humid, southeastern United States, with a number of studies focusing on more arid portions of the country (Stabler et al., 2005; Harlan et al., 2006).

This study utilizes a network of surface observation stations to provide an understanding of temperature variability within an urban setting. Such networks are highly beneficial in understanding the complex interactions amongst environmental conditions in a highly heterogeneous environment (Grimmond et al., 2010; Muller et al., 2013), and add critical data to this field of study in light of the concerns expressed in such literature as Ho et al. (2016) on the use of satellite derived land surface temperature data. This study builds on previous work by focusing on the warm, humid, southeastern United States, by providing high temporal resolution data over a range of seasons, and by employing high resolution land cover information. The goal of this study was to analyze Knoxville's microclimates over the course of an entire year to answer two primary questions: (1) how do climates vary within a medium-sized city in the southeast United States, and (2) can differences in impervious surface and tree canopy coverage explain the temperature variability identified.

## 2. Study area/design

This study takes place in Knoxville, Tennessee, USA. With an estimated population of 184,281 as of 2014 1 July, it is the third largest city in Tennessee (USCB, 2016). Its climate is classified by Koppen-Geiger as humid subtropical, which is a humid, warm temperate climate with hot summers (Cfa) (Kottek et al., 2006). Average yearly precipitation is 1215.6 mm, 165.1 mm of which is in the form of snow. The average maximum temperature of 31.2 °C occurs in July and the average minimum temperature of −1.6 °C occurs in January. The average yearly mean temperature for Knoxville is 15.3 °C (NWS, 2016).

Ten identical weather stations were installed in July of 2014. Two weather stations were installed in each of four urban neighborhoods: West Hills, Lonsdale, Burlington, and Vestal (Fig. 1, Table 1). Additionally, two stations were installed at locations in downtown Knoxville and at Ijams Nature Center, a forested park within the Knoxville Urban Wilderness. The four urban neighborhoods were chosen based on their relative proximity to downtown, differing socioeconomic makeup (USCB, 2016), and varied land cover characteristics evidenced by differential tree cover and impervious surface percentages. To minimize confounding factors, locations were chosen that had similar altitude and topographical features.

Within each neighborhood, two locations were chosen to provide extremes in terms of the magnitude of localized tree cover. One station was in a location with minimal tree cover ("Clear"), and one was located within denser tree cover ("Tree"). The differences in tree canopy in Clear and Tree locations were explored, verified, and quantified as described in the Methods section.

## 3. Methods

### 3.1. Data collected

Each weather station consisted of Onset Smart Sensors connected to a HOBO Micro Station Data Logger (H21-002). The logger was housed within a Cantex Junction Box (20 × 20 × 10 cm) and installed at an average height of 2.25 m above ground. The Onset 12-bit Temperature/Relative Humidity Smart Sensor (S-THB-M002) measured temperature with a range of −40 °C to 75 °C, had an accuracy of ± 0.21 °C, a resolution of 0.02 °C, and was placed inside a solar radiation shield attached to the side of the box. The weather stations were tested together in a temperature controlled environment prior to installation to ensure consistent readings across all units. Readings were taken over a 30 min period every 5 min and then analyzed for systematic error using the methodologies of Taylor and Kuyatt (1994). The error was found to be approximately 0.03 °C. Thus, conservatively, temperature differences between sites of less than twice this value (0.06 °C) cannot be confidently asserted.

Temperature data were logged every five minutes and manually collected from the logger. Data analyzed herein were collected between 2 July 2014 and 1 July 2015. Data were unavailable at select stations for various periods of time due to either vandalism or station malfunction, ranging from 6 to 30 days. Despite this, there were 295 total days available where data were present for all ten stations, with all seasons being well represented, resulting in a robust data set for analysis.