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Inter-annual variability in urban heat island intensity over 10 major cities in the United States

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ABSTRACT

Urban heat island intensity (UHI) has become a cross-cutting quotient to characterize the thermal environment of urban areas. In this study, we use publicly available weather data from ten metropolitan centers located in US to characterize the hourly, seasonal and yearly variability in air temperature based UHI. Our results reveal that while there are phenomenological similarities on UHI causes and trends, their order of influence in different cities is however distinct. Of cities compared here the coastal and arid cities exhibited high diurnal variability during the summer months. During the cold season, except for New York City, other cities had a flatter profile. Our analysis also shows that during extreme heat days in the warm season, the UHI is amplified in most cities. The UHI of cities located along the coast was highly sensitive to sea breeze and in general experience more extreme heat days than the inland cities.

1. Introduction

UHI is a measure of the impact of urbanization on the local thermal environment and is a quintessential factor that dictates weather patterns (Oke, 1995) and several ecosystem functions that affect the local energy and the hydrological cycles (Arnfield, 2003). The large scale anthropogenic modification of the land cover in urban areas has lead to surfaces that are efficient in storing heat (Grimmond & Oke, 1999) as opposed to moisture, and a geometry that assists in radiative trapping (Kusaka, Kondo, Kikegawa, & Kimura, 2001; Lemonsu, Grimmond, & Masson, 2004; Masson, Grimmond, & Oke, 2002). In addition, combustion from vehicles and waste heat (Gutierrez, Gonzales, Martilli, & Bornstein, 2015) from buildings contribute to create a thermally aggravated environment. This modification directly impacts energy-use and human health (Grimmond et al., 2010). UHI, for the most part is used as an indicator by physical and health scientists to quantify the amplified thermal state of the urban environment, lately even urban planners, architects (Shishegar, 2014) and industry stakeholders alike are invested in understanding the influence of UHI to abet smart and sustainable design. The convergence of interests from various fields has expanded the applicability of the UHI quotient across various socio-economic and scientific dimensions. Hence it is crucial to adequately account for UHI and its variability across multiple spatial and temporal domains.

Due to the high prevalence of remotely sensed infrared images from satellites, many studies resort to surface temperature based UHI (Chen, Zhao, Li, & Yin, 2006; Dixon & Mote, 2003; Yue, Liu, Fan, Ye, & Wu, 2012). These studies explicitly relate the trends in UHI to urbanization and urban sprawl by analyzing a history of images for a particular space over a period of time (Weng, 2001). This methodology has two main shortcomings; surface temperature does not necessarily translate to air temperature, owing to uncertainties in estimating the turbulent transfer rates and secondly the observations are often discontinuous in temporal scale (Harris & Coutts, 2011). However the satellite data is highly useful in spatially mapping the impact of urbanization albeit to surface temperature. There exists two methods to quantify UHI based on air temperature; one through direct observations (Gaffin et al., 2008; Gedzelman et al., 2003) and the other through numerical weather modeling (Ramamurthy, Li, & Bou-Zeid, 2015). The numerical models are the most effective as they have both high spatial and temporal resolution, however it is computationally expensive to run these models for extended periods of time (Mirzaei & Haghighat, 2010). Most urban scale simulations are carried for no more than a week or exclusively focus on events like heatwave episodes (Gutiérrez, Gonzales, Arend, Bornstein, & Martilli, 2013). While observational networks are restricted by sensor density they can be used to track

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Nomenclature

UHI	Urban heat island intensity (°C)
MSA	Metropolitan statistical area
Tu	Urban temperature (°C)
Tr	Rural temperature (°C)
Rn	Net radiation
H	Sensible heat flux ($W m^{-2}$)
LE	Latent heat flux ($W m^{-2}$)
G	Storage flux ($W m^{-2}$)

monthly and seasonal changes. In this study our main objectives are to:

1) Understand the variability in UHI over various temporal scales at different cities using data from multiple observational networks.
2) Quantify the impact of extreme heat events on UHI during the observational period.

Ten metropolitan areas are observed here for a period of 10 years (2005–2014) to understand the spatial and temporal variability in UHI. The comparative analysis will aid us to qualitatively assess the factors that impact UHI at various geographic locations and will also help us to quantify the inter-annual, seasonal and daily trends.

The analysis presented here will have immediate benefits to the urban planning, healthcare organizations and the power sector. The power companies need accurate estimation of the state of the thermal environment (Declet-Barreto, Brazel, Martin, Chow, & Harlan, 2012). It is estimated that a 0.55 °C increase in ambient air temperature over a mid-sized US city will lead to 2–4% increase in electricity load (Akbari, Pomerantz, & Taha, 2001) and this additional demand will lead to blackouts and brownouts (Grimmond, 2007). The average distribution of hourly UHI intensity will help the companies gauge the variability in power demand at different times during the day. Many city administrations are aggressively pursuing to reduce the UHI and have put forth ambitious plans like cool roofs and pavements and green roofs and urban greening to moderate the urban temperature (Akbari, Konopacki, & Pomerantz, 1999). Information on monthly and seasonal trends will help these agencies to quantify the potential benefits of various adaptation strategies.

2. Methods

The analysis relies on publicly available data from the National Weather Service's automated surface observing system. Table A1 in the Appendix describes the stations that are used for this analysis. The table also details the location and the landcover surrounding the station. Ten years of continuous air temperature data, spanning from 2005 to 2014 is used for this analysis. Multiple stations are used for every city and are averaged based on their time stamps. Due to discrepancy in the retrieval times at each site, data from each stations are binned hourly. Multiple rural reference stations are picked to calculate the UHI. These rural stations are influenced by the same climatology as urban stations and are also approximately located at the same altitude. The UHI value for each city is calculated using the following equation;

$$UHI(t) = \frac{1}{n}\sum_{i=1}^{n1} T_{ui}(t) - \frac{1}{n}\sum_{i=1}^{n2} T_{ri}(t) \quad (1)$$

In the above equation for anytime 't', the UHI is the difference between the average of all urban air temperatures (T_{ui}) from different stations and the average of all rural air temperatures (T_{ri}) (pikes and erroneous data points are neglected from the analysis.). Ten cities are selected for this analysis and their locations are indicated in Fig. 1. The 10 cities are picked from different climatic zones from across the US. Of the cities, NY (New York City), LA (Los Angeles), Seattle, and Houston are coastal cities. The climatology's of these cities, based on Köppen-Geiger (Peel, Finlayson, & McMahon, 2007) are listed below;

- NY, Houston, Washington DC and Philadelphia experience humid subtropical climate (Cfa) with NY the northernmost city in the humid-subtropical zone.
- Chicago, Atlanta and Dallas experience humid continental climate (Dfa).
- Seattle and LA on the West Coast are in a subtropical Mediterranean zone (Csb), although precipitation deficits could make LA close to a semi-arid climate.
- Phoenix experiences arid climate (BWh). It receives around 200 mm of rainfall annually.

The cities analyzed here serve as centers of larger metropolitan statistical areas (MSA) and are important socio-economic engines in their respective regions. The 10 cities fall in the top 15 largest MSA's in the US according to the US census Bureau (US Bureau, 2011), with NY being the largest with a combined population of 23 million people and Phoenix the smallest (14th largest in the US) with 4.3 million people. NY is also the densest and most populous city with nearly 8.5 million people living in 783 km^2. The NY metropolitan area is home to nearly 23 million people and covers the states of New York, New Jersey and Connecticut. In total, nearly 81 million people reside in the MSA's analyzed here, which is around 25% of the total US population. In terms of area, Houston, Phoenix and LA are the largest in size, 1550 km^2, 1340 km^2 and 1200 km^2 respectively. Washington DC is the smallest of all the cities with an average area of 158 km^2.

3. Results

The results section is organized in to four subsections: the first discusses the 10-year variability in summertime air temperature, the second investigates the average daily variability in UHI during Summer months, the third details the UHI variability during Winter months and the fourth section highlights UHI variability during extreme heat events.

3.1. Decadal variability in urban temperature

The panel box plots in Fig. 2 shows the inter-annual variability in warm season (June, July and August) temperature over 10 cities in the United States. All the urban stations in each city are averaged to produce the box plot. The top edge represents the 75th percentile and the bottom edge of the box indicates the 25th percentile value. The top and the bottom edge of the whiskers denote 95th and 5th percentile respectively. The diamond inside the box indicates the mean temperature and the dash indicates the median value of the distribution. To enhance readers perception, the box plots are color coded; the spectrum of green shades emphasize the inter-annual variability in mean temperature with darker shades representing relatively higher annual average.

The panel box-plots reveal lesser yearly variability in temperature in Seattle and Los Angeles, both of which are situated along the pacific coast, compared to the rest of the cities. This shallow year-to-year variability is very much related to the moderation due to the ocean effect, emphasizing the role played by the coastal winds.

One consistent theme is discernible in the year-to-year variability in temperature among the cities. Year 2014 is the hottest