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Research Paper

How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago

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HIGHLIGHTS

- Combined fourteen physical measures to estimate elevated air temperatures.
- Determined that nighttime and daytime UHIs are driven by different variables.
- Higher daytime winds make nighttime UHIs easier to predict than daytime UHIs.
- Identified waste heat's significant role in increasing daytime temperatures.

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ABSTRACT

Urban Heat Islands (UHI) are urban and suburban areas with elevated surface and air temperatures relative to surrounding rural areas. This study combines variables from the remote sensing and urban climatology publications to explain UHI intensity in eight Chicago neighborhoods. During the summer of 2010, we collected air temperature measurements within an urban block in each neighborhood. Consistent with remote sensing research that measures surface temperature, the predictors of elevated nighttime air temperatures were land cover variables. At 2 a.m., the urban block's percentages of impervious surface and tree canopy explained 68% of the variation in air temperature. At 2 a.m., the other physical measures of urban canyon and street orientation were not significant. At 2 a.m. during extreme heat events, the urban block's percentages of impervious surface and tree canopy explained 91% of the variation in air temperature. At 4 p.m., the only significant explanatory variable was distance to industrial sites and this explained 26% of the variation in air temperature. At 4 p.m. during extreme heat events, there were no significant predictors. We believe this research illustrates the importance of differentiating time of day for residential and non-residential areas in UHI mitigation efforts and the need to include waste heat in future UHI investigations.

1. Introduction

Cities have the ability to modify their climates. These modifications include changing cloud cover, precipitation patterns, wind speeds, solar irradiance, and increasing air temperatures (Oke, Johnson, Steyn, & Watson, 1991; Santamouris, 2001). The most significant modification is the creation of Urban Heat Islands. The term Urban Heat Island (UHI) refers to an urban area with temperatures that are elevated relative to its less developed surroundings. While the physical mechanisms causing UHIs are well documented (Oke, 1987), they continue to be the most studied phenomenon in urban climatology (Johnson et al., 1991; Oke, 1973; Stewart, 2011). One reason for urban climatologists' continued interest is that the known physical mechanisms dynamically interact with each city's contextual characteristics, such as its biophysical features, urban development pattern, local weather patterns, and adjacent water bodies.

Urban planners, urban designers, public health officials, and city decision-makers are increasingly concerned with UHIs as research reveals that urban areas are warming at a faster rate relative to their surrounding rural areas and UHIs amplify heat extremes (Stone, 2012). While planners, designers, and decision-makers want to identify the most significant causes of UHI, most seek a simplified method appropriate for neighborhood-level interventions but one that does not require remote sensing analysis. By combining measures of land use/land cover, building configuration, and adjacent heat sources and sinks that are easily collected, we seek a practical

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set of metrics to understand the key drivers of elevated urban air temperatures.

After a brief discussion of UHIs, we review how factors of land use/land cover, building configuration, and adjacent heat sources and sinks contribute to surface and air UHIs. This review provides the basis for our selection of 14 independent variables of interest. Next, we summarize the contextual characteristics of Chicago, a city in a temperate climate and grassland biome that is adjacent to Lake Michigan. Then we describe our selection of eight Chicago neighborhoods and collection of daytime and nighttime summer weather data. Using regression analysis, we identify the independent variables that explain the largest proportion of the neighborhood air temperature variation by time of day. We repeat this analysis for a heat event. We conclude with a discussion of the results and their contribution to the UHI literature.

While known studies of UHIs date back to Luke Howard's research in London in the early 1800s, the term first emerged in the meteorological literature in the 1940s (Stewart & Oke, 2012). UHIs are not limited to large cities but exist within settlements as small as 1 km^2 (Imhoff, Zhang, Wolfe, & Bounoua, 2010). Although climate change is contributing to rising urban temperatures, Stone (2012) determined that most large US cities are warming twice as fast as the planet. Stone believes that land-use change and waste-heat are contributing more toward this warming than global climate change. No matter the confluence of causes, UHIs will increasingly threaten the liveability and safety of urban environments. While the maximum UHI temperatures occur in late afternoon, public health research has determined that nighttime minimum air temperatures are the strongest predictor of heat-related mortality (Kalkstein & Davis, 1989). Therefore, useful UHI research needs to consider nighttime minimum air temperatures as well as daytime maximums.

Much of the research into UHIs can be coarsely divided into broad scale approaches that use remotely sensed satellite images to locate UHIs by surface temperature and fine-scale approaches that use small weather stations or mobile measurement devices to determine UHIs using air temperatures. Surface temperature variations are greatest during the day but air temperature variations are greatest during the night (Lo & Quattrochi, 2003). In the following section, we begin by highlighting relevant findings from a few remote sensing studies that examine how different land use and land cover variables explain land surface temperature. Then, we transition to finer-scale investigations from urban climatology that measure air temperatures to determine how three-dimensional built configuration and adjacent heat sources and sinks impact the UHIs.

1.1. Land use/land cover

Typically remote sensing studies examine the impacts of land use/land cover changes by examining what percentage of the surface temperature can be explained by the presence of impervious surface (building roofs and pavements), vegetation indices, and surface characteristics such as elevation and topography (Lo & Quattrochi, 2003). Research based on remote sensing has effectively documented both the magnitude and spatial distribution of UHIs across broad regions and the heat trapping properties of many building and paving materials. In the following paragraphs, we highlight some of the key results that have emerged from remote sensing research on the UHI.

Imhoff et al. (2010) used remotely sensed images of 38 of the most populated urban areas within the continental United States to understand the influence of development density, spatial extent of the city, and bioclimatic region on surface temperature. Partitioned into grid cells, each city's urban area was defined by grid cells with more than 25% impervious coverage. Across these 38 US cities in eight bioclimatic regions, the percentage of impervious surface explained approximately 70% of the land surface temperature. Among the cities, the amount of variance explained by the percentage of impervious surface varied from 60 to 90%. The authors concluded that the areas of urban impervious surface explained the extent and intensity of the UHI more accurately than earlier techniques that used the city's total population (Oke, 1973). They also found that the city's surrounding bioclimatic environment influenced the magnitude of the UHI. The magnitude of the UHI was greater (6.5–9 °C) in areas that had displaced forested environments relative to temperate grasslands and savannas (6.3 °C) and tropical grasslands (5 °C). So urban areas in temperate climates may have greater UHI intensity relative to semi-arid and arid areas. While this research confirmed the importance of impervious surface as an important indicator and the influence of ecological context on the UHI's magnitude, Imhoff and colleagues (2010) note that their work does not capture the finer-scale microclimate variations that result from different ecological patterns within cities.

Two earlier remote sensing studies illustrated that UHI are not always concentrated in the urban core and may be dispersed throughout urban and suburban areas. Lo and Quattrochi (2003) published a remote sensing study that examined how land use/land cover changes in the thirteen county Atlanta Metropolitan Area altered the location and intensity of UHIs. The researchers identified six land use/land cover types: high-density urban use (largely commercial and industrial), low-density urban use (largely residential), cultivated or exposed land, cropland or grassland, forest, and water. During the twenty-five year period of rapid city expansion, areas of high-density and low-density land use increased by 90 and 119% respectively while areas of forest and cropland decreased by 21 and 33% respectively. In summer 1987, DeKalb County (near the center) was the hottest county and Cherokee County (northern edge) was the coolest. However, by summer 1997, the hottest county was Gwinnett (northeast edge) and the coolest was Cowetta County (southwest corner). With the changes in land use/land cover in metro Atlanta over a ten year period, the region developed four predominant UHIs (Lo & Quattrochi, 2003). By the late 1990s, suburban areas overtook areas near downtown Atlanta to become the region's warmest locations.

The irregular distribution of the UHI within cities is also related to vegetation and, in some locations, socioeconomic neighborhood patterns. In Phoenix, Arizona, Jenerette et al. (2007) found that temperature differences within the metropolitan area varied systematically with neighborhood-level social characteristics. Poorer neighborhoods were significantly hotter. Every $10,000 increase in neighborhood annual median household income was associated with 0.28 °C decrease in the surface temperature at 10 a.m. on a May morning. A multivariate model using path analysis showed that the cooler temperatures associated with higher income neighborhoods were primarily the result of increased vegetation cover. In this semi-arid location, few plants (native or exotic) self-propagate and in poor neighborhoods, residents generally cannot afford to buy plants or water. While we generally recognize the installation costs of vegetation, writers seldom mention that poorer households in arid and semi-arid locations may not be able to maintain vegetation due to water costs. This study also underscored that the presence of pervious surfaces does not always imply vegetation by default. Most importantly, this study alerts us to the concern that UHIs may disproportionately burden the city's poorest residents.

All types of vegetation are not equally effective in mitigating the UHI. Grass is not as effective as trees that cast shade and contribute more moisture. Stone and Norman (2006) determined that if the suburban areas of Atlanta reduced their lawn areas by 25% and replaced them with trees, they could reduce the contribution of unwanted heat to UHIs by 13%.