Evaluating Neighborhood Environments for

Urban Heat Island Analysis and Reduction

by

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**A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Urban and Regional Planning)
in the University of Michigan
2013**

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ACKNOWLEDGMENTS

I would like to thank the following people and organizations for helping me through the dissertation process:

- Larissa Larsen, my committee chair, my advisor, and mentor for her support, guidance, and encouragement through the Masters and PhD process
- My other committee members Richard Norton, Scott Campbell, Marie O'Neill for their encouragement and thoughtful insight
- the Graham Environmental Sustainability Institute for funding and mentoring support
- Wesley Waggener, Sue & Tom Coseo for your support and encouragement through the process
- Nick Rajkovich for counsel and building the weather tricycle,
- Marie O'Neill for use of the HOBO weather stations
- the Office of the Vice President the University of Michigan for funding the weather tricycle
- the Chicago Department of Transportation, especially Janet Attarian & David Leopold for their support of this research
- ComEd, and ATT&T for granting me permission to locate the weather stations on your utility poles

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ABBREVIATION	
CDOT	Chicago Department of Transportation
Dist	Distance
EPA	Environmental Protection Agency
Fwy	Freeway
GAP	Green Alley Program
Indust	Industry
ISA	Impervious surface area
LEED	Leadership in Energy and Environmental Design
LULC	Land use and land cover
NWS	National Weather Service
Orien	Orientation of urban canyons
UBL	Urban boundary layer
UC	Urban canyon ratio
UCL	Urban canopy layer
UHI	Urban Heat Island
USGS	United States Geological Survey

Chapter 1

Abstract:

City officials are increasingly concerned about heat. Two warming processes are increasing the occurrence of urban heat: 1) global warming caused by greenhouse gas emissions and 2) intensifying urban heat islands (UHI) caused by urbanization. Global climate change increases the frequency, intensity, and duration of hot days. UHIs result in warmer urban air temperatures relative to rural and suburban areas Problems directly resulting from hot weather and UHIs include increased heat mortality, infrastructure failure, increased stress to vegetation, and decreased air and water quality. City officials are increasingly taking action to analyze and reduce UHIs. Yet, past research provides insufficient information for researchers and planners on 1) the relative contribution of neighborhood physical characteristics to UHIs and how those physical characteristics' contribution may change during different times of day, 2) the accuracy of land cover quantifications necessary to predict UHIs, and 3)monitoring the performance of in-situ cool pavement strategies. To address these gaps in the literature, I conducted three related studies of UHIs in eight Chicago neighborhoods in 2010. 1) I found that light winds at night resulted in stronger relationships between independent neighborhood physical variables and UHI intensity (2 a.m., adjusted R^2 = 0.68) than during the afternoon (4 p.m., adjusted R^2 = 0.26). At night land cover variables were better predictors of UHIs relative to other factors. Yet, during the afternoon, I found that upwind heat sources were better predictors of UHIs relative to other factors. 2) In the second study, I found that coarse (two-dimensional) quantifications of impervious surface area are sufficient for UHI prediction. Even so, more detailed (three-dimensional) quantifications that document impervious surfaces concealed by tree canopy are likely better for urban forestry and planning for rights-of-way. 3) Finally, I found that out of six different cool pavement strategies, highly reflective concrete and pervious concrete, cooled the air. Both designs had cooler air at three meters by at least -0.40°Ccompared to conventional asphalt paving. As city officials move to implement initiatives to reduce UHIs, this research provides a useful direction on how to conduct UHI analysis and monitor the performance of UHI reduction strategies.

Introduction

This research involves the urban heat island effect. The urban heat island effect (UHI) is the warming of air due to the physical properties of urban land covers and the altered ventilation patterns due to building configurations. Urban areas generally have warmer air temperatures relative to rural or suburban areas (Stewart, 2011; Solecki et al., 2005). It is important to differentiate UHIs from the effects of global warming but to also understand how these distinct phenomena interact. Essentially two types of warming are occurring in cities: 1) global climate change and 2) urban-induced warming or UHIs (Stewart, 2011; Stone, 2012). Global climate change is caused by the release of greenhouse gas emissions and it is increasing average temperatures. Global climate change is also increasing the number, frequency, intensity, and duration of extreme heat days. Extreme heat days are defined as days when the maximum apparent temperature or heat index (combining both heat and humidity) exceed the 85^{th}

percentile of average long-term temperatures (Sheridan et al., 2009; Stone et al., 2010; Gaffen & Ross, 1998). Unlike global climate change, UHIs are caused by the conversion of rural land to urban land covers (Stone, 2012). However, UHI exacerbate extreme heat conditions and are seen by city officials as a growing public health threat (Stone, 2012; EPA, 2012c; Berg, 2012; LBNL Heat Island Group, 2012; Kaufman, 2011; Niiler, 2012; Badger, 2012; Sreenivasan, 2012).

Problems directly resulting from the combination of UHIs and heat events include increases in heat mortality and morbidity, increased infrastructure failure, increased drought and fire threat, increased stress to urban vegetation, changes to regional precipitation patterns, decreased urban air quality, and reduced outdoor quality of life for city dwellers (Gartland, 2008; Stone, 2012; Baik et al, 2001). Death rates in past heat events in Europe approached 70,000 dead in the 2003 heat waves and 800 dead in Chicago in 1995 (Stone, 2012, Wuebbles et al., 2010, Hayhoe et al., 2010b). This is especially problematic since recent studies have shown that lower-income residents and racial minorities are more likely to live within UHIs (Santamouris et al., 2007; Harlan et al., 2006) and thus are disproportionately burdened by the negative effects. Stone (2012) reminds us that often these problems combine to magnify the societal costs, such as when power grid failures create urban water shortages by disabling pumping stations. For these reasons city officials are moving to implement UHI reduction plans, often as adaptation components within Climate Action Plans.

This dissertation consists of three complimentary articles examining how neighborhood environments impact the magnitude of UHIs and what strategies might lessen the negative effects. All three articles are intended to provide researchers and planners with a guide to evaluate urban climates at the neighborhood or microclimate scale. Chapter two reviews the relevant literature from urban climatology, urban design, and the heat vulnerability literature. Chapter three examines how physical characteristics of eight Chicago neighborhoods differentially contribute to UHIs. Chapter three provides direction on how urban planners may evaluate and predict neighborhood microclimate conditions. Chapter four examines how the accuracy in land cover characterization alters the precision of UHI assessment. Finally, chapter five quantifies the impact of different cool pavements intended to reduce UHIs. This work is timely and relevant because municipalities, non-profit environmental organizations, and private property owners are promoting, installing, and taking action to reduce UHIs and the threats from extreme heat. In fact, the Environmental Protection Agency (EPA, 2012c) lists at least 75 local, state, and private initiatives to address UHIs. These actions range from small private projects such as the Ford River Rouge greenroof and cool paving program in Dearborn, MI to more comprehensive programs such as the seven active initiatives by the city of Chicago. In addition private accreditation organizations such as U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) ratings system have developed credits to encourage UHI reduction strategies. While, LEED credits reward developers for installing UHI reduction strategies, little research evaluates the specific performance of such strategies. Researchers, planners, designers, and city officials require better information on how to analyze UHIs and how UHI reduction strategies perform. This dissertation intends to address these requirements.

Chapter 2

Literature Review

In this section I identify the gaps in three areas of research for which this study addresses: 1) the study of urban climates, 2) the design of urban places that create UHIs, and 3) heat, humidity, and public health implications of UHIs. In addition, I discuss Chicago's urban climate and its efforts to reduce the UHI through the Green Alley Program.

This research responds to researchers and practioners needs to evaluate urban environments for UHI reduction. This research lies at the intersection of physical planning and urban design, urban climatology and meteorology, and the public health impacts of extreme heat. In this literature review, I identify three gaps in the literature and then, in the following chapters, I proceed to examine each in detail through the research. These gaps can be written in the form of three research questions:

1. What is the relative contribution of land cover, neighborhood building configuration, and adjacent heat sources and sinks to UHI development in a temperate city? In addition, how do the physical characteristics impact UHIs at different times of day and during heat events?
2. Does highly detailed three dimensional measurement of urban land cover significantly improve UHI characterization over less detailed two dimensional measurements?
3. To what extent do in-situ cool pavements reduce air temperatures compared to conventional pavements?

1.0 Urban climate

Urban climate research examines the atmosphere in direct contact with urban land covers (Oke, 1987). This section examines 1) how researchers define urban climates from non-urban climates, 2) UHIs during warm weather, and 3) the societal problems created by UHIs.

Urban climate research has identified three key components of the atmosphere over cities: 1) the planetary boundary layer (PBL), 2) the urban boundary layer (UBL), and 3) the urban canopy layer (UCL). The planetary boundary layer (PBL) is the bottom portion of the troposphere that interacts with the earth surface. The atmosphere interacts with rougher urban land covers causing it to slow down due to increased friction thus forcing air upward (Oke, 1987). Upward forcing not only occurs because of slowing of air, but also because of the warmer urban land covers. Due to these two processes, the PBL varies in thickness by day and night. During the day the PBL is generally one to two km (3280.8 to 6561.7 ft.) thick, while at night the PBL can constrict to 0.1 km (328 ft.) under stable conditions (Oke, 1987). Within the planetary boundary layer, Oke (1987) has identified 2 layers critical for understanding urban climate: the *urban boundary layer* (UBL) and the *urban canopy layer* (UCL). During the day the UBL extends from the top of buildings up 0.6 to 1.5 km (1968.5 to 4921.3 ft.) and decreasing to 0.1 to 0.3 km (328 to 984 ft.) at night due to increased stability (Oke, 1987). The UBL controls regional atmospheric patterns including precipitation, air pollution, and transport of heat energy from the UCL below (Oke, 1987). Although not in direct contact with urban land covers, the UBL plays an important role in an area's air quality. Past research has pointed to the UBL as an important mechanism in regional transport of hazardous air pollution linked to UHIs such as ozone production (Gray & Finster, 2000). However, it is important to note that in some regions wind patterns in the UBL decouple UHIs from ozone sources. Gray & Finster (2000) found that ozone non-compliance days were not directly linked to UHI locations thus displacing the impacts of ozone from heat source areas to other downwind regional centers (Gray & Finster, 2000).

The UCL occurs beneath the UBL and is the area below the height of buildings to the earth's surface. The UCL is where urban microclimates occur and affect everyday life. The thicknesses of the UCL vary depending on the heights of buildings. The UCL establishes atmospheric conditions below the roof level of buildings or tree canopy to the ground surface (Oke, 1987).

Both the UCL and UBL are heavily influenced by the physical characteristics of the ground surface. These characteristics control reflectivity and energy balance properties, and thus directly and indirectly heat the UCL and UBL respectively. Urban climate research has found that urban physical characteristics control local microclimates. Therefore planning and design decisions that influence these characteristics influence and change urban climates.

1.1 Defining UHIs

UHIs are a warming of the UCL and UBL relative to adjacent cooler locations (Solecki et al., 2005). UHIs are produced by 1) urban land covers, 2) neighborhood building configuration, and 3) adjacent heat sources and sinks (Oke, 1987; Oke, 2006; Bonacquisti et al., 2006; Stone, 2012; Jenerette et al., 2007; Stewart, 2011). UHIs are measured using either land surface temperatures or air temperatures between two or more locations. Typically, the *UHI intensity* (ΔT) is measured as the difference in surface or air temperatures between an urban and a rural location (Stewart, 2011). Past research has shown that UHIs increased air temperatures by 5^{o}C in Rome, Italy (Bonacquisti et al., 2006), 6.5 ^{o}C in Shanghi, China (Djen et al., 1994), 7 ^{o}C in London, United Kingdom (Wilby, 2003), and as much as 12 ˚C in Lodz, Poland (Klysik & Fortuniak, 1999). Based on the literature, we have learned that these differences are associated with the influence of an area's urban physical characteristics.

Over the past forty years we have also learned that UHIs are not a simple urban-rural gradient. Urban areas may contain numerous heterogeneous UHIs that change by season, diurnally, and with weather conditions. UHI are not isolated to the urban downtown core (Bonacquisti et al., 2006; Stewart, 2011; Jenerette et al., 2007). For example, Memon & Leung (2010) reported that Hong Kong's mean temperature difference between urban and rural areas is 2^{o}C in winter and 0.5^{o}C in summer, but they have measured maximum air temperatures differences as high as 10^{o}C. In addition, UHI patterns vary by region (Imhoff et al., 2010), occur in more dispersed pattern than once thought (Harlan et al., 2006, Bonacquisti et al., 2006), and may increase or decrease over time (Stone, 2012; Akbari et al., 2001). Imhoff and colleagues (2010) investigated UHI patterns in eight different biomes in the U.S. and found that the largest UHIs (on average 8^{o}C) were in cities located in temperate broadleaf and mixed forest regions where evapotranspiration played a key role in cooling. Bonacquisti and colleagues (2006) show that

Rome's UHI most frequently occurs as two distinct heat islands with a large park at the center of Rome creating the pattern. Akbari and colleagues (2001) report that since 1940 that urban air temperatures in U.S. cities have increased between 0.5–3.0^{0} C on average. They found that most of this warming was the result of intensifying UHIs.

Understanding UHIs requires isolating the urban warming effects from other warming influences such as weather, regional air patterns, water bodies, or topographic effects (Stewart, 2011; Oke, 2006; Stone, 2012). This is challenging because these other warming effects complicate the formation and distribution of UHIs (Jenerette et al., 2007; Gaffin et al, 2008, Gray & Finster, 2000). Since urban areas contain complex UHI patterns researchers face trade-offs when picking base weather stations to describe an area's UHI intensity. Common factors that may affect the isolation of urban factors include the distance from rural areas to urban neighborhoods due to sprawling urbanized regions, changes in topography between rural and urban locations, and the distance of rural locations from important regional moderating mechanisms such as bodies of water. In extensively urbanized regions, it may be necessary to choose more urban weather stations that lie closer to the neighborhoods of interest for calculating UHI intensity.

Researchers and planners are most concerned about UHIs in hot weather. UHIs are not as problematic in cool weather and may even have the benefit of reducing heat bills and cold-related mortality in cold weather (Oke, 1988; Santamouris et al., 2007). However, during hot weather UHIs enhance heat waves and produce a host of negative societal impacts. Stone (2012: 78) found that a July 1999 heat wave enhanced Chicago's UHI by 3-4^{0} F. Not only were urban centers hotter on average, but during heat waves the difference or UHI intensity was amplified (Stone, 2012).

Planners address the physical characteristics that influence UHIs because of their concern for the negative impacts of increased heat (Gartland, 2008; Memon et al. 2007; O'Neill et al, 2005; Harlan et al., 2006; Stone, 2012; EPA_b, 2012).. High air temperatures associated with UHIs directly 1) increase heat related illnesses and deaths, 2) decrease air and water quality, 3) decrease urban soil quality and tree health by drying soils, and 4) lead to failures in infrastructure. In addition, high air temperatures indirectly 5) increase energy and water as residents use air conditioning and additional irrigation to cope with the heat, which also contributes to even higher air temperatures. Finally, high heat indirectly 6) increases energy use and leads to the release of more waste heat. Elevated temperatures make neighborhoods not only uncomfortable but they cause potentially deadly consequences for vulnerable residents. Deaths from heat surpass all other natural disasters combined in terms of mortality (NWS, 2009). Mechanical buffers such as air conditioning can be a buffering resource to cope with hot temperatures and poor air quality (O'Neill et al., 2005). Yet, not all residents are able to afford air conditioning (Santamouris et al., 2007). In some hot regions residents have little choice but to use air conditioning to stay cool. O'Neill and colleagues (2005) found that African Americans in four northern cities (Chicago, Detroit, Minneapolis, and Pittsburgh) had a 5.3% higher heat mortality rates than Whites. The use of air conditioning explained 64% of the difference in heat-related deaths (O'Neill et al., 2005). In addition, the excess cost to use the technology can lead to utility poverty (the added burden of high energy bills in relation to income) (Santamouris et al., 2007). Societies' reliance on air conditioning to buffer residents from high temperatures also contributes to poor air quality and additional warming due to global climate change.

Electricity use increases during heat events due to the additional use of air conditioning by residents trying to keep cool. Yet, electricity is often produced from coal or other fossil fuels that emit chemicals leading to the development of ground level ozone. The additional electrical generation along with fossil-fuel burning automobiles produces nitrogen oxide (NOx) and volatile organic compounds (VOL) emissions. The combination of high air temperatures plus sunlight, NOx and VOL forms ozone (Stone, 2005). Modeling land use change in six Midwestern states, Stone and colleagues (2007) showed that overall if compact development could increase mean census tract density by 10%, the average number of vehicle miles traveled could be cut back by 3.5% and thus result in lower emissions. This is important because Stone and colleagues (2010) found that growth in number of extreme heat days was connected to physical characteristics of urban form. They found that from 1956 to 2000 the average number of extreme heat days per year in compact cities grew by only 5.6 days, where more sprawling cities grew by 14.8 days per year. Heat is a key component in producing poor air quality. Higher air temperatures allow the atmosphere to not only hold more pollution particulates, but also heat is a key factor in the chemical reaction necessary to produce ground level ozone.

Finally, hot temperatures and related weather patterns tend to disable or shorten the life cycle of important infrastructure that keeps urban areas cool, including electricity for air conditioning and urban trees. Power grids fail, concrete roads buckle, asphalt melts, rail lines warp, and trees wither and die in the heat (Stone, 2012). Stone (2012) makes the point that these foundational urban infrastructure systems typically fail when we need them most during heat events. Increased electricity demand during heat events puts extra stress on our regional power grid systems. Stone (2012) reports that power grid failures in the U.S. are increasing each year on average by 16%. When these occur during heat waves, they raise resident's exposure to heat as air conditioning no longer serves as a buffering resource to keep residents cool from high temperatures. In the Europe 2003 heat wave, Stone (2012) describes the failure of different urban infrastructure elements including the shutdown of nuclear power plants due to insufficient water for cooling, derailment of a train in Britain due to warping of the tracks, and the withering of urban trees. Urban forest can be at risk from extreme heat. Modeling of trees has shown that near 40^0C (104^0F) evapotranspiration rates drop off dramatically as the plants begin to protect themselves from heat stress by conserving water (Dimoudi & Nikolopoulou, 2003). City officials are becoming increasingly concerned with the negative impacts from UHIs and moving to implement UHI reduction programs that include changes to the physical characteristics of neighborhoods. Yet, gaps in the current research leave city officials with an incomplete understanding of how the urban design of neighborhoods contribute to UHIs.

2.0 Urban design - contribution to UHIs

The physical design of urban places contributes to UHIs. The purpose of this section is to summarize the physical factors that influence the development of UHIs including 1) an area's urban materials, 2) three general categories of physical drivers that influence UHI formation, and 3) physical design strategies to reduce UHIs.

2.1 The physical properties of urban materials

Typical urban materials include concrete, asphalt, metals, glass, and other artificial materials. These urban materials change the reflectivity and energy balance of land covers in several important ways. First, urban materials in U.S. cities reflect only a small portion of incoming solar radiation. Taha (1997) found that only 15 -20% of the incoming shortwave radiation was reflected by urban areas in the U.S., while the remaining 80-85% was absorbed and stored by urban materials. A measure of a materials reflectivity is called its albedo. The albedo is a ratio of the incoming shortwave solar radiation to the reflected outgoing radiation. Measured from 0 - 1.0, materials close to 0.0 reflect almost none of the incoming solar radiation, absorbing close to 100% of the incoming energy. New asphalt may have albedo values of 0.05 (EPA_a, 2012). New asphalt may also absorb close to 95% of incoming radiation. Second, urban materials alter the energy balance of land covers. Emissivity is the measure of a material's ability to store and emit heat energy. It is measured from 0 - 1.0, where materials that approach 1.0 efficiently store heat releasing it slowly to the atmosphere. Concrete, asphalt, and brick emissivity values are around 0.90 (Golden & Kaloush, 2006). Yet, some research has pointed to the limited role emissivity plays in affecting UHIs (Doulos et al., 2004; Oke et al., 1991).

Finally, the heat energy stored in urban materials is emitted in one of three forms: 1) sensible heat, 2) longwave radiation, or 3) latent heat. Both sensible heat and longwave radiation contribute to higher air temperatures. Sensible heat energy raises air temperatures by the process of convection (Stone, 2012; Gartland, 2008). The convection process accelerates with higher wind speeds, more air turbulence, and larger temperature differentials between urban materials and the UCL (Gartland, 2008). Longwave radiation warms the air indirectly through the greenhouse effect (Stone, 2012). Latent heat does not contribute to warmer air temperatures. Latent heat is formed through the process of evaporation. Stored heat energy evaporates moisture and in the process it is transformed to undetectable latent heat. Without the presence of moisture latent heat is not formed and heat is released as sensible or longwave radiation. For this reason moisture from soils and from plants play important roles in providing cooling. Lack of moisture is caused by high amounts of impervious surfaces that seal out soil moisture and replace vegetation with urban materials.

2.2 Three general physical design categories that drive UHI formation

This section covers the three general physical design categories that influence UHI formation: 1) land cover factors, 2) neighborhood building configuration factors, and 3) adjacent heat sources and sink factors.

2.2.1 Land cover

The first category of physical drivers that influence UHIs formation is the conversion of land cover from rural to urban covers. Specifically, UHI formation is influenced by the relative proportion of urban impervious surface to natural vegetated land covers. As urban areas develop and density increases, impervious pavement and building surfaces replace permeable soils and vegetation. Dimoudi & Nikolopoulou, (2003) found that in dense Athens neighborhoods that for every 10% increase in the percentage of vegetation to highly impervious areas resulted in a decrease in air temperature by 0.8^{0}C. Impervious surfaces limit the presence of moisture, which plays a key role in moderating local air temperatures.

Impervious pavements and buildings make up a substantial percentage of land cover areas in U.S. cities. Imhoff and colleagues (2010) found that in 38 U.S. metropolitan regions impervious surfaces accounted for nearly 80% of the land in compact downtowns. Downtown Sacramento had 81.55% impervious surface area in its downtown (Akbari et al., 2003). Estimates of roof cover in seven New York City neighborhoods range from as low as 18.1% to as much as 45% of the land cover (Rosenzweig et al., 2006). Over four of the largest metropolitan regions in the U.S. (Salt Lake City, Sacramento, Chicago, and Houston) pavements accounted for nearly 40% of the total urbanized region (Akbari et al, 2009). Estimated impervious pavements in seven New York City neighborhoods varied 38.2 to 50.8% of the total neighborhood area (Rosenzweig et al., 2006). Gray & Finster (2000) found that pavements accounted for 18.32% to 25.62% of total Chicago neighborhood area (Gray & Finster, 2000). Impervious surfaces result in a host of environmental problems related to UHIs.

Large areas of impervious surfaces exacerbate at least three environmental problems related to UHIs: 1.) dry urban environments, stormwater flooding, and reductions in water quality, and 2.) more intense UHIs (Hough, 2004; Alberti, 2009; Stone, 2012; Gartland, 2008; Imhoff et al., 2010). As the percentage of impervious surfaces increase in an area there is less planting area for healthy vegetation, which results in less moisture from plants (Hough, 2004). In addition, warm pavements cause urban soils to dry more rapidly than rural soils not only putting further stress on plants but further exacerbating the dry urban climates (Stone, 2012). Pavements seal off rainwater and air from entering or leaving soils. This further restricts moisture available for cooling. Rain falling on impervious pavements collects on the warm impervious surface instead of soaking into the soil. Collected run-off, warmed by urban surfaces, may result in flooding and degradation of local streams and water bodies (EPA_d, 2012). Finally, impervious materials change the reflectivity and energy balance of surfaces resulting in locally higher air temperatures or UHIs (Gartland, 2008; Stone, 2012). For this reason vegetation and permeable soils play a critical role in moderating and dampening the warming effects of impervious land covers in urban environments. Zhang and colleagues (2011) found that percent impervious of 17 Detroit area sites explained 59% of the variance in average daily minimum air temperatures (5 a.m.), yet at 5 p.m. percent impervious surface was not significant. They found that for every 10% increase in impervious surface area, average minimum temperatures at 5 a.m. were 0.40^{0}C warmer (Zhang et al., 2011)

The two main processes by which vegetation contributes to cooling are through 1) evapotranspiration and 2) shade (Dimoudi & Nikolopoulou, 2003; Shashua-Bar & Hoffman, 2000). Dimoudi & Nikolopoulou (2003) modeled vegetation's impact on air temperature for an urban block in Athens. They showed that in Mediterranean climates maximum evapotranspiration rates occur with wind speeds of 1.0 m/s at 25^{0}C. As wind speed increases to 10 m/s the maximum evapotranspiration rate occurs at a slightly higher temperature. Yet, as air temperatures approach 40^{0}C evapotranspiration rates plummet, reaching lower levels than during winter months. This occurs in order for the plant to avoid heat stress. At higher temperatures, plants shut down evapotranspiration to conserve water. This makes tree shade an important cooling mechanisms in urban environments. Shashua-Bar & Hoffman (2000) found that in Tel-Aviv on average 80% of the 3.23 ^{0}C reduction in air temperatures from trees was due to the tree's shade. Yet, the impact of both shading and evapotranspiration likely varies by time of day. Hamada & Ohta (2010) found percentage of tree canopy in Nagoya, Japan had a significant negative correlation explaining 72% of the variance in air temperature at 1:00 a.m. and 57% at 3:00 p.m. In this case, air temperature decreased by 0.34^{0}C at 1 a.m. and 0.43^{0}C at 3:00 p.m. for every 10% increase in tree canopy. At 8:00 a.m. they found only a weak correlation with tree canopy explaining only 9% of the variance in air temperatures. Researchers use remotely sensed images to quantify urban area's land cover types to understand the impact of impervious and vegetative land covers on UHIs.

Researchers use remotely sensed images to classify and calculate land covers using 1) two-dimensional, 3) three-dimensional, or 3) ground based approaches. The two-dimensional approach classifies land covers from a top-view and does not differentiate between types or levels of vegetation on the image. Tree canopy is classified as a land cover type and ground level land covers beneath the tree canopy are not included in the calculations (Akbari et al., 2003). Using this approach, Solecki and colleagues (2005) found that in in the six New Jersey neighborhoods tree canopy cover varied from 10% to 26%, impervious surfaces varied from 18% to 30% (Solecki et al., 2005). Yet, in the neighborhoods with 26% tree canopy it is likely that a significant amount of pavements, roofs, and other impervious surfaces went undocumented. A three-dimensional approach accounts for land covers under tree canopies and sometimes even wall surfaces (Rose et al., 2003; Akbari et al., 2003; Nichol & Wong, 2005). Using a three-dimensional approach greatly improves the classification of land cover types (Akbari et al., 2003). Akbari and colleagues (2003) used both a two and three-dimensional approach to calculating land cover in downtown Sacramento, CA. They found that accounting for under the tree canopy impervious surface raised the amount of impervious surface by over 17% (from 64% to 81.6% impervious surface coverage). A similar analysis of medium density Chicago neighborhoods by Akbari & Rose (2001a) found that grass areas, roads, parking lots, and sidewalks were the most commonly missed land covers. Finally, at a very fine scale some researchers have used ground surveys to calculate and classify land cover classes (Chang et al., 2007). A more common practice is to use ground surveys to ground-truth remotely sensed data (Geneletti & Gorte, 2003). Yet, from past research it is not clear what level of accuracy is needed for land cover calculations in order to improve the explanatory power of UHI models.

2.2.2 Neighborhood building configuration

The second category of physical drivers that influence UHI formation are a neighborhood's building configuration. Past studies conflict on the degree to which a neighborhood's building configuration impacts local air temperatures (Stone et al., 2007; Stone & Norman, 2006). Studies that support the influence of building configuration have shown that the heights of buildings, building density and arrangement, and street/alley orientation impact local temperatures (Oke et al., 1991; Oke, 2006; Eliasson, 1996; Sakakibara, 1996). Researchers use several measures to gauge an area's building configuration contribution to UHIs including an area's building heights, urban canyon ratio, sky view factor, and orientation (north-south, east-west) of urban canyons. Building heights not only determine the height of the UCL but also impact solar access, shading, and radiational cooling (Oke, 1987). A more sophisticated measure than building heights is the urban canyon ratio. The urban canyon ratio is the height of buildings divided by the width of street (h/w). This measure tries to improve upon building heights alone to account for the way urban canyons regulate ventilation, solar access, and the amount of radiational cooling at night. Past studies have shown that urban canyon ratio is a significant predictor of surface and air temperatures within the urban canyon (Sakakibara, 1996; Eliasson, 1996). In addition, Oke and colleagues (1991) found that urban canyon walls contributed roughly the same amount of heat energy as impervious surfaces to elevated air temperatures.

Another measure of building configuration is the sky view factor (SVF). SVF is the ratio of sky obstructed by buildings, trees, and other objects divided by the total potential sky (flat horizontal plain) at a particular location. Thus SVF varies from 0 - 1.0, where 1.0 is 100% unobstructed sky on all horizons. Most significantly, a location's SVF impacts radiational cooling (Eliasson, 1996; Svensson, 2004). Svensson found that in Gotenborg, Sweden SVF readings ranging from 0.34 - 0.98 explained 58% of the variance in air temperatures (Svensson, 2004). Yet, by looking at only the densest urban canyons with SVF between 0.22 - 0.66 she was able to raise the explanatory power up to explaining 78% of the variance in air temperatures. Finally, researchers use an urban canyon's orientation to measure its effect on air temperature. Urban canyon orientation affects primarily building shading and ventilation patterns (Saaroni et al., 2000). Sakakibara (1996) found that a Tokyo east-west street's north facing canyon wall absorbed the most shortwave energy between 8-9 a.m. and that it cooled by 2 p.m. South facing canyon walls absorbed solar energy most of the day only cooling after sunset (Sakakibara, 1996). Ali-Toudert & Mayer (2007) found that models of Ghardaia, Algeria east-west oriented streets had higher temperatures than north-south due to the lack of shading over the course of the day. The same study found that simulating a 5 m/s breeze parallel to the urban canyon reduced the apparent temperature by 12^{0}C (Ali-Toudert & Mayer, 2007). Although some research shows the influence of building configuration on UHIs, other research has produced conflicting results.

Another stream of research has shown that compact building configuration does not significantly contribute to UHIs compared to other influences (Stone, 2012; Stone et al., 2007; Stone & Norman, 2006). Stone & Norman (2006) found that tree canopy played a critical role in reducing the release of sensible heat in suburban Atlanta. They found that if 25% of the lawn area in suburban Atlanta were replaced with trees, the contribution from sensible heat would be reduced by 13% (Stone & Norman, 2006). The role of each category of factors such as land cover and compact neighborhood building configuration depends on regional cooling mechanisms such as tree canopy (Imhoff et al., 2010). Some researchers have found that in certain regions the conversion of natural land to urban land cover is more influential than building configuration to the development of UHIs (Stone, 2012; Stone et al., 2007; Stone & Norman, 2006; Imhoff et al., 2010). Especially if compact building configuration efficiencies, such as lower energy use and waste heat, are taken into account (Stone, 2012; Stone et al., 2007; Stone & Norman, 2006). From past research it remains unclear the role that neighborhood building configuration plays in its contribution to UHIs.

2.2.3 Adjacent heat sources and sinks

The third general category of physical drivers that influence UHI formation are adjacent heat sources and sinks. The influence of upwind locations plays a larger role in determining local air temperatures as wind speeds increase displacing air temperatures to downwind locations (Kljun et al., 2004; Britter & Hanna, 2003; Voogt & Oke, 2003). Under light winds the physical area influencing air temperatures may be small. Yet, as winds increase the zone of physical characteristics that influence air temperatures increases in area. Thus, air temperature readings at a particular location may be more influenced by upwind location's physical characteristics than the physical characteristics of the immediate area. Air temperature readings may largely depend on upwind source location's physical characteristics, the height of the weather sensor, amount of atmospheric turbulence, surface roughness of the buildings, wind direction and speed (Kljun et al., 2004; Voogt & Oke, 2003; Oke, 2006). For analysis of adjacent heat sources and sinks researchers have found that the shape of the source area is roughly equivalent to an ellipse. Yet, in reality an upwind heat footprints' shape are heavily dependent on upwind physical characteristics that influence air transport (Voogt & Oke, 2003; Oke, 2006). Understanding air transport from heat sources such as waste heat from cars or industry or cool sink areas from vegetation or water is particularly important because many heat event days occur on windy days, displacing the heating effects to adjacent neighborhoods. Grimmond & Oke (2002) calculated source areas for an air temperature sensor located at heights between 18 and 45 + meters to be between 0.15 km^2 and 5 $km^{2.}$ The large range in the area of influence is because a source/ sink area's size is dependent on atmospheric stability, wind speed, and the surface roughness. Oke (2006) provides a general guide that the source area footprint of a sensor placed at three m. height extends in an elliptical shape up to 0.5 km upwind from the sensor.

Some research has indicated that anthropogenic waste heat contributes from 1 to 5^0 C to UHIs (Fan & Sailor, 2005; Shashua-Bar & Hoffman, 2000). Kato & Yamaguchi (2005) found that in Nagoya, Japan, sensible heat from anthropogenic sources was highest during summer and winter with much lower spring and autumn values. Taha (1997) estimated that, in the Chicago region, anthropogenic waste heat sources accounted for up to 53 watts/m^2 of sensible heat contribution to urban heating. Waste heat from air-conditioning is particularly problematic because of the feedback loop. Higher UHIs result in more need for air-conditioning and therefore produce more waste heat. Akbari & Taha (1992) found that the UHI increased the air-conditioning peak electricity demand in five U.S. cities between 5 to 10%. Congested freeways may play an important role in contributing anthropogenic waste heat from idling vehicles to certain neighborhood UHIs, especially during times of rush hour traffic (Britta & Hanna, 2003). Shashua-Bar & Hoffman (2000) found heavy trafficked streets in Tel-Aviv traffic accounted for up to 2^0 C of warming. Since waste heat is linked with human activity, proximity to these sources of waste heat, predominant wind direction, and lack of atmospheric ventilation may place certain neighborhoods at greater risk of higher UHI intensity during specific times of day.

Many of the world's cities lie on water bodies that influence local temperatures and UHI patterns. The presence of water in urban environments alters temperatures by increasing local relative humidity, affecting wind direction, and introducing a cooling maritime effect of water bodies. Trying to measure the impact of large water bodies on air temperature, Memon and colleagues (2009) found that hourly relative humidity readings were negatively correlated with air temperature and explained 70% of the variance in air temperature difference. However, aggregating the data to monthly values eliminated much of the explanatory power ($R^2 = 0.07$). In addition, a later study by Memon & Leung (2010) in Hong Kong found that wind speed explained 80% of the variance in air temperature. They found in Hong Kong that for every +1.0 m/s increase in wind speed the air temperature cooled by 1.9^{0}C (Memon & Leung, 2010). Saaroni and colleagues (2000) found that cooler areas of Tel-Aviv were likely to include plazas, wide roads, and large intersections. They speculate that the lower temperatures are a result of sea breezes that are more able to penetrate areas of the city with a more open character. Compactness of buildings not only affects penetration of maritime influences, but compactness also may affect how neighborhoods warm during the day and cool at night.

From this review of the three physical categories that influence UHI formation we learn that two main gaps remain. First, conversion of natural vegetated to impervious land covers appears to be the most significant driver of UHIs (Stone, 2012; Imhoff et al., 2010). Yet, many studies only looked at impervious surface areas in isolation from other important factors such as neighborhood building configuration and adjacent heat sources and sinks. In addition, although time of day was examined in two studies, it was limited only to vegetation and impervious surface variables (Hamada & Ohta, 2010; Zhang et al., 2011). Related to this, researchers disagree on the role neighborhood building configuration plays in contributing to UHIs (Oke et al., 1991; Stone et al., 2007; Stone & Norman, 2006; Stone, 2012). Some researchers claim neighborhood building configuration plays a significant role in warming urban environments (Eliasson, 1996; Svensson, 2004; Sakakibara, 1996; Saaroni et al., 2000; Ali-Toudert & Mayer, 2007). Yet, often these studies examined building configuration in isolation of land cover and adjacent factors. Other researchers, examining building configuration in relation to land cover, have shown that land cover plays a larger role in warming urban environments (Stone et al., 2007; Stone & Norman, 2006; Stone, 2012). Second, in the past most researchers used a coarse two-dimensional approach to quantify land covers, but land covers lie on multiple planes and are often obscured by tree canopy in dense urban neighborhoods. Using a three-dimensional approach improves the quantification of land cover variables, but it is unclear whether this improves the explanatory power of UHI models. More accurate UHI models are useful to understand how implementing UHI reduction strategies will impact elevated neighborhood air temperatures.

2.3 Strategies to reduce UHIs

The purpose of this section is to review the common UHI reduction strategies with an emphasis on cool pavement strategies. The U.S. Environmental Protection Agency advocates changes to land cover factors to reduce UHIs. Suggested UHI reduction strategies include highly reflective and green roofs, highly reflective and permeable pavements, and adding vegetation (Golden et al., 2007, EPA_b, 2012). For the most part, changes to neighborhood building configuration and adjacent heat sources and sinks are more difficult issues to tackle. Making changes to a neighborhood's existing building configuration is problematic. Planning history in the U.S. had many unsuccessful urban renewal efforts attempting to significantly alter the scale of buildings and a neighborhood's building configuration. In addition, adjacent upwind areas may be outside of a jurisdiction or have complicated political obstacles to making changes. This makes changes to land cover variables much easier to implement than changes to a neighborhood building configuration. Most UHI reduction strategies used by cities today are based on changes to land cover factors.

Three main land cover UHI reduction strategies are commonly used: 1) cooling with vegetation, 2) cool roofs, and 3) cool pavements. Most researchers examining the effects of UHI reduction strategies have used computer models to simulate the effects of the strategies (Rosenzweig et al., 2006; Pomerantz et al., 2000; Akbari et al., 2001; Solecki et al., 2005). Compact urban neighborhoods typically have a lot of impervious surfaces; at least some areas of unused pavements can be found and removed. Street trees may be planted in pits in impervious pavement areas. Rosenzweig and colleagues (2006) used simulations to estimate the amount of space available for tree planting and how that tree planting could decrease air temperatures in New York City neighborhoods. They found that at least 17% of the city's surface area was available for street tree planting. If the tree planting was implemented, they estimate that the additional trees would reduce air temperatures by up to -1.8^0F on average at 3 p.m. (Rosenzweig et al., 2006). Yet, some impervious surfaces will need to remain. This makes both cool roofs and cool pavements necessary. Rosenzweig and colleagues (2006) estimated that installing green roofs or raising the reflectivity of roof surfaces in seven New York City neighborhoods may result in reduction in air temperatures from as little as -0.60^{0}F to as much as -1.8^{0}F.

Two types of cool pavement in use to reduce UHIs are 1) highly reflective pavements and 2) permeable pavements. Highly reflective pavements absorb less incoming solar radiation than conventional pavements. Simulations raising the reflectivity of pavements in Los Angeles by 25% could reduce pavement surface temperatures in Los Angeles by as much as 10^{0}C (Akbari et al., 2001). Fewer studies have examined the cooling benefits of permeable pavements (Haselbach et al., 2011; Nakayama & Fujita, 2010). Permeable pavements reduce air temperatures by increasing the convective cooling of the pavement material due to the increased surface areas of the voids and increasing the evaporative cooling from moisture in the voids and soil (Greenroads, 2012). Haselback and colleagues (2011) found that the voids in pervious pavements held stormwater and this increased the loss of stored heat energy by as much as 13 Joules / cm^{2} over conventional pavements. What many of these studies have in common is that most use real world calculations of the physical characteristics of neighborhoods or regions, but then use simulations to predict cooling without taking in-situ air temperature measurements. The gap in the literature is that many of these studies have been conducted on cool pavement techniques in controlled settings, but less studied is in-situ cool pavement performance. In addition, the impact of pavement temperatures on air temperatures under various wind speeds has received little attention. This is important because past research has shown that UHIs tend to be most intense under clear skies with light wind conditions (Djen et al, 1994: 2126; Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999; McPherson et al., 1997).

3.0 Heat, humidity, and public health implications of UHIs

Although extreme heat produces a host of other societal impacts, planners are most concerned about extreme heat and UHIs because of the public health implications. This section examines 1) past heat-related mortality events, 2) heat awareness efforts, 3) how UHIs exacerbate heat stress and illnesses, 4) frameworks for conceptualizing heat vulnerability, and 5) important times for heat exposure.

Past heat waves in Russia resulted in over 15,000 estimated deaths in the 2010 and over 70,000 estimated deaths in the European heat waves of 2003 (Masters, 2010; Hayhoe et al., 2010b). Yet, these are estimates because heat is seldom listed as the cause of death (Sheridan et al., 2009). Sheridan and colleagues (2009) explain that a common practice in environmental epidemiology is to report heat related mortality numbers as those mortalities that depart from normal. Only reporting deaths that have been declared as a result of heat has been shown to undercount heat-related deaths (Sheridan et al., 2009). This is because heat triggers other ailments that are then officially listed as the cause of death such as heart attacks, strokes, or fatal asthma attacks.

Local public health officials use public awareness campaigns to inform residents of the dangers from extreme heat. The National Weather Service (NWS) plays a key role in informing the public of dangerous weather and providing alerts for extreme heat. Most U.S. weather forecasts are based on primary weather data from the NWS. The NWS issues heat advisories, watches, and warnings based on the heat index developed by Steadman (1979). When temperatures exceed 26.7 ^{o} C (80 ^{o} F) with a relative humidity of 40%, a person generally begins to feel hotter than the recorded air temperature (Steadman, 1979). This is roughly the same mean maximum temperature threshold 27 ^{o} C (80.6 ^{o} F) that Kalkstein & Davis (1989) found to be significant in increasing heat-related mortality in the Chicago region. Over this threshold, the National Weather Service issues heat alerts based on the heat index or the apparent temperature in an effort to inform the public of the likelihood of heat disorders with prolonged exposure. In order to communicate the exposure danger of combined heat and humidity conditions, the NWS warns residents by issuing heat alerts based on the heat index classification system. Above 26.7 ^{o} C (80 ^{o} F) residents are alerted to use *caution*, above 32.8 ^{o} C (91 ^{o} F) they should use *extreme caution*, above 39.4 ^{o} C (103 ^{o} F) heat reaches a *danger* level, and finally above 52.2 ^{o} C (126 ^{o} F) residents are warned of the *extreme danger* from heat (NWS, 2009). Yet, this index is calculated based on locations in the shade with light wind conditions, so these probably underestimate many urban locations with low tree canopy where limited shade and stronger winds can increase heat index exposure values by as much as 15°F (NWS, 2009). This is especially problematic as areas susceptible to UHIs tend to have lower percentages of shade from tree canopy and higher solar exposure rates (Solecki et al, 2005).

Past studies have shown that UHI and heat events couple to create dangerous conditions for neighborhood residents (Harlan et al., 2006). Stone (2012) compared urban to rural air temperature trends over 50 years for the 50 largest American cities to determine if urban areas were warming faster. He found that, on average, UHIs make these urban areas +1.5^{0}F warmer than rural areas and this average difference is increasing at a rate of +0.14^{0}F per decade (Stone, 2012). Therefore UHIs in the U.S. are intensifying over time. Past work has not only illustrated the spatial differentiation of UHIs, but also how they change diurnally and with weather conditions. Many studies have illustrated the strengthening of UHI intensity during the overnight hours under light wind conditions (Memon et al., 2009; Oke et al., 1991; Djen et al., 1994). Djen and colleagues (1994) measured the UHI intensity of Shanghai and found it to be most extreme during times of weak winds when air exchange between urban and rural atmospheres became reduced or limited. They confirmed that the strongest UHI intensity was observed at night in the presence of light winds when surface heat storage was more efficient at heating the lower canopy layer through longwave and sensible heat energy (Djen et al, 1994: 2126). In Chicago, maximum daytime UHIs often shifts toward western suburban locations because of the Lake breeze, but at night winds reverse to a land breeze bringing higher temperatures back toward downtown overnight (Gray & Finster, 2000). This is problematic because night is an important time for residents' bodies to cool down and receive a break from high temperatures. If air temperatures remain high, near 37^{0}C, the human body cannot cool down adequately putting physiological stress on a person, which can lead to heat stress, illness or in the worst case death (Solecki et al., 2005).

Eakin & Luers (2006) identify four aspects that may make residents more vulnerable to heat related illnesses. These aspects are a 1) person's individual characteristics, 2) their social networks/isolation, 3) a person's access to material buffers/resources such as air conditioning, and 4) where a person lives including physical characteristics. Thus a key role planners' play is to address the physical characteristics of a neighborhood to reduce UHIs. Planners influence regulations and policies that determine the physical characteristics of a neighborhood and thus in part influence local UHIs. Recent research has pointed to multiple physical characteristics that raise a person's heat vulnerability. Factors that raise someone's heat vulnerability include older housing stock, living on the top floor, and more intense UHIs (Duneier, 2006). The year in which a person' home was built can affect the type of cooling possible in the home. Pre-World War II housing units were commonly built without air conditioning. This lack of air conditioning may make it more difficult or expensive to mechanically cool these homes. Recent studies have shed more light on the dispersed patterns of UHIs that tend to disproportionately affect lower-income residents and racial minorities (Santamouris et al., 2007; Harlan et al., 2006, Solecki et al., 2005; Jenerette et al., 2007) and thus burden those communities with the negative health outcomes resulting from exposure to higher temperatures.

Three key areas for researchers to look at for public health are 1) extreme heat events, 2) times of day when residents are more at risk to heat illness, and 3) income disparities. First, since areas with UHIs are hotter than other areas on average, during heat events people living in these areas are at even higher risk of heat exposure. Heat events are periodic weather conditions that may persist from a day or two to several weeks (Sheridan et al., 2009). Gaffen & Ross (1998) define heat event days as days where the maximum apparent temperature (how it feels with a combination of heat and humidity) exceeds the 85th percentile of average long-term temperatures (Stone et al., 2010). Yet, past research has also shown that late night and the time of maximum afternoon heating are critical windows of exposure during heat events (Kalkstein & Davis, 1989; Solecki et al, 2005). The highest air temperatures typically occur in the late afternoon. At this time of day, indoor or outdoor activities without cooling relief may result in heat stress. Nights are cooler than days, but past research has shown that hot weather conditions at night are dangerous. One study found that heat at night was the greatest predictor of heat-related mortality (Kalkstein & Davis, 1989).

Finally, past research has found that in some regions UHIs aligns with income and disproportionately expose poor resident to higher air temperatures (Jenerette et al., 2007; Santamouris et al., 2007; Solecki, et al., 2005). The research points to the important role of vegetation in moderating air temperatures. Poorer neighborhoods were affected by higher UHI intensities than wealthier neighborhoods mostly as a result of a lack of vegetation in the poor neighborhoods. Vegetation reduces air temperatures from shade and evapotranspiration. Yet, most poor residents cannot always afford to pay for the expense of vegetation and irrigation to maintain healthy plants (Solecki et al., 2005; Jenerette et al., 2007). A Phoenix study found that for every $10,000 increase in neighborhood annual median household income was associated with 0.28^{0}C decrease in the surface temperature at 10am on a May morning (Jenerette et al., 2007). Although past research has shown that UHIs disproportionately affect lower income neighborhoods, researchers have not adequately addressed this pattern in moist temperate climates where vegetation does not necessary align with income.

The major gap for public health research is the lack of studies on how heat event days and different times of day affect the relationships between the physical characteristics of a neighborhood and UHIs. Past studies have found poorer residents may have a greater exposure to heat due to UHIs, but more regions need to be examined. In addition, most UHI public health research concerned with the physical drivers of UHIs are conducted at coarse census tract or larger scales, not at the fine scale of neighborhood blocks. It is important for planners and researchers to understand how the physical factors that contribute to UHIs may change during heat events and during the two critical times of day for heat exposure (late night and the time of maximum afternoon heating). Planners need to understand if income disparities are found in bioregions with more moisture and vegetation. This is useful information that planners may use to prioritize UHI reduction strategies and target vulnerable residents

4.0 Chicago's urban climate

The purpose of this section is to review Chicago's regional climate and the physical characteristics that influence the city's urban climate. Chicago's urban climate and UHIs are heavily dependent on the city's 1) flat coastal landscape, 2) urban forests, and 3) urban density and land cover. First, the city of Chicago sits on a lake plain at the southeast corner of the Lake Michigan (41^0 52' 55" North and 087^0 37' 40" West (USGS$_a$, 2012)). The elevations within the city limits varies by only 28.6 m (from 176.5 m (579 ft.) to 205.1 m (673 ft.) above sea level) (USGS$_b$, 2012). Generally, the region's moderate mid-continental climate averages a mean summertime (May to September) temperature of 25.9^{0}C (1961-1990)(Hayhoe et al., 2010$_a$). Yet, the region is prone to large temperature swings. Record highs have reached 105^{0}F on July 24, 1934 with record lows of -27^{0}F on January 20, 1985 (NWS Chicago Records, 2012). Important moderating influences in summer include Lake Michigan and tree canopy. During summer Lake

Michigan cools areas adjacent to Lake Michigan. Yet, by July and August the water temperature rises to reduce this influence. On July 6, 2012, Lake Michigan's south buoy registered the earliest recorded 26.7 ^{o} C (80 ^{o} F) water temperature reading (NWS Chicago, 2012). This record surpassed the old records set in 2011 and 2010 by two weeks. As climate change accelerates it appears as though the cool effect of Lake Michigan may be diminished.

Trees also play a key role in moderating Chicago's climate. Historically, the region lies within the mid-continental temperate grasslands, savannahs and shrubland biome (Imhoff et al., 2010). Yet, urbanization has resulted in increased forest cover from 13% in presettlement times to 20% as of the mid 1990s (McPherson et al., 1997). Several land cover studies have been conducted of the Chicago region (McPherson et al., 1997; Gray & Finster, 2000; Akbari & Rose, 2003a; Nowak & Greenfield, 2012). A more recent study by Nowak & Greenfield (2012) found that the region's tree canopy had decreased from 20% (McPherson et al., 1997) in the mid-1990s to 18% by 2009. In addition, of the 20 cities Nowak & Greenfield analyzed, Chicago had a lower tree canopy in 2009 than other cities (average for 20 cities was 28.2%). Yet, when the analysis looks only at the city of Chicago, percentage of tree canopy drops even further. McPherson and colleagues (1997) found in the mid-1990s the city of Chicago averaged roughly 11% tree canopy. Akbari & Rose (2001a) found that Chicago's tree canopies varied from a low of 3.7% in Pilsen to a high of 13% in Wrigleyville.

The region's population of 9,461,105 is up 4% over the past 10 years, with continued expansion of urbanized areas at the rural fringe of the metropolitan area (U.S. Census, 2012). Although the City of Chicago has seen a resurgence of new urban residents in parts of the City within the last 20 years, the 2010 population of the City is down 6.9% from 2000 to 2,695,598 residents (US Census, 2012). Chicago's average population density in 2010 was 45.7 persons per hectare (18.5 persons per acre) within the City limits. This density was down from 49.2 persons per hectare (19.9 persons per acre) in 2000 and 51.1 persons per hectare (20.7 persons per acre) in 1980 (U.S. Census, 2012). Even though Chicago's population density is down, its land cover types and building configuration were largely established with initial development of streets, alleys, and buildings in the late 1800s and early 1900s and remain largely unchanged.

Gray & Finster (2000) analyzed 14 areas in the Chicago region and found that low to medium density Chicago neighborhoods (Rogers Park, Lincolnwood, Wrigleyville, Garfield Park, Lincoln Park, Cicero, Pilsen, Stone Island, and Oaklawn) had on average 44.1% to 46.4% vegetative surfaces. Impervious surfaces in these neighborhoods ranged from 48.12% to 83.3% of the total area (29.8% to 36.9% roofed surfaces and 18.3% to 25.6% paved surfaces) (Gray & Finster, 2000). Many of the neighborhoods with the highest percentage of impervious surfaces were within close proximity of the downtown Loop.

Compared to other large U.S. cities, Chicago's UHI is largely influenced by continental regional weather patterns that bring a combination of moist warm air from the Gulf of Mexico combined with hot air domes from the central and southern plains. These weather patterns combine with local influences most importantly Lake Michigan to influence local UHI patterns. Gray & Finster (2000) found that average maximum daily temperatures from April to October 1992-1996 were displaced from the downtown area by Lake Michigan's influence and the maximum daytime UHI occurred in the western suburbs, centered over Lisle, IL.

Based on research, Chicago's summertime air temperatures are expected to increase in severity and duration (Coffee et al. 2010). Hayhoe and colleagues (2010_a) used statistical downscaled models to understand how mean temperatures from May - September at Midway Airport would change in low and high greenhouse gas emission (GHG) scenarios. Under the low emissions scenario Midway Airport's mean daily average summertime air temperature will shift from a mean of 25.9^0C (1961-1990) to 28.9^0C by 2100. Under the high emissions scenario that rises to 32.2^0C by 2100 (Hayhoe et al., 2010a). One study found that in a high GHG emission scenario, the number of days above 37.8^0C (100^o F) per year in Chicago is likely to increase from two (2) days per year (1961 – 1990 average) to thirty-one (31) days per year by 2070 (Chicago CAP, 2008; Vavrus & Van Dorn, 2010). Heat indices may also increase more rapidly as warmer air is able to hold more moisture thus increasing the apparent temperature (Wuebbles et al., 2010). Chicago's urban climate and UHIs will likely be exacerbated by global climate change and continued urbanization in the region.

To address the growing risk from extreme heat and UHIs, according to the EPA (2012c) Chicago has at least seven active initiatives to address UHIs. The larger initiatives include: 1) the Chicago Urban Heat Island Mitigation Program that serves as an umbrella program by the Chicago Department of Environment to initiate programs and install demonstration projects to reduce UHIs; 2) the Chicago Energy Conservation Code that changes building codes to require highly reflective and lower emissivity roof surfaces; 3) the Chicago Department of Transportation's (CDOT) Green Alley Program (GAP) to convert public alleys from conventional asphalt pavements to highly reflective and permeable pavements; 4) the Chicago Roof Grants Program providing $6,000 grants to residential and commercial property owners to install green or cool roofs; 5) the Chicago Green Roof Program to incentivize the construction of green roofs; 6) the Chicago Landscape Ordinance to require the planting of trees and vegetation in rights-of-way, parking lots, and other vehicular use areas; 7) the Chicago Landscaped Medians Program overseen by the CDOT to increase tree cover and vegetation on new and existing medians throughout the city. Chicago is taking action to reduce UHIs even though the science behind analyzing UHIs and UHI reduction efforts are incomplete.

Chicago's Green Alley Program (GAP) began in 2006 to address stormwater and UHIs. Although the main goal of the GAP was stormwater management (Buranen, 2008), the City is attempting to address UHI reduction. The alleys served as a testing ground for the CDOT to experiment with alterative cool pavement designs. The two main pavements used in the program to reduce UHIs were 1) highly reflective concrete and 2) permeable pavements (CDOT, 2009). As of December 2009, the city had installed over 100 alleys. The CDOT was able to reduce the cost of green alleys through in-house research and design of cool pavement technologies so it is now comparable to conventional alley design (Attarian, 2010). For this reason, green alley design is now the standard for alley reconstruction. CDOT monitors and evaluates the program on an ongoing basis. In part, this research is intended to contribute to the evaluation of the GAP.

The findings from these three studies are particularly applicable to comparable mid-continental temperate cities with similar urban physical characteristics**.** Yet, the general frameworks for these studies are more generalizable to other non-temperate cities. The physical characteristic categories of land cover, neighborhood building configuration, and adjacent heat sources and sinks are useful for other researchers and planners looking to evaluate local microclimates. In addition, the methods to quantify land cover areas and evaluate Chicago's cool pavement program are applicable to any type of city.

5.0 Gaps in the literature

This dissertation responds to three gaps in the study of UHIs. First, it addresses the lack of guidance for the relative contribution of physical characteristics planners need to document to predict neighborhood UHIs. Past research has lacked clarity on the relative contribution of land cover factors in relation to neighborhood building configuration and adjacent heat sources and sinks. Connected to this UHI research does not adequately account for the ways in which the physical characteristics might contribute to UHIs differently at night and during the time of maximum heating especially during hot weather conditions. Second, past studies have used two and three-dimensional approaches to quantifying land cover variables. Yet, the research does not address if the more accurate but laborious three-dimensional quantifications of land cover increase the explanatory power of UHI models. Finally, past research has generally evaluated cool pavement performance with computer simulations or in controlled laboratory settings. Missing from the research are studies examining in-situ cool pavement performance and the impact of pavement temperatures on air temperatures under various wind speeds

Chapter 3

How Factors of Land Cover, Building Configuration, and Adjacent Heat Sources and Sinks Differentially Contribute to Urban Heat Islands in Eight Chicago Neighborhoods

Abstract:

The Urban Heat Island (UHI) is defined as elevated surface and air temperatures in urban areas relative to surrounding suburban and exurban areas (Solecki et al., 2005). Problems that result from the UHI include decreased air quality, increased heat mortality, increased energy and water use, failure of infrastructure, and altered regional precipitation patterns (Stone, 2005; Gartland, 2008; Baik et al, 2000). This study examines how different physical features measured at the neighborhood scale contribute to the UHI intensity in eight Chicago neighborhoods. During the summer of 2010, I collected air temperature measurements in neighborhoods selected to represent different land cover mixes, neighborhood building configurations, and adjacent heat sources and sinks. Consistent with coarse-scale investigation that rely on surface temperature proxies, the predictors with the most explanatory power of elevated air temperatures at night were land cover variables. I found that light winds at night resulted in stronger relationships between the physical characteristic variables and UHI intensity at 2 a.m. (adjusted R^2 = 0.68) than at 4 p.m. (adjusted R^2 = 0.26).. At night percent impervious was a better predictor of UHIs relative to building configuration. The relationships changed during the day. The significant predictor of UHI intensity shifted to upwind adjacent factors during the afternoon likely due to higher wind speeds. During the afternoon I found that a neighborhood's distance to upwind industrial areas was a better predictor of UHIs relative to land cover factors. This research is an important contribution to understanding how municipalities embarking on UHI reduction should prioritize limited financial and political resources to reduce the heat vulnerability of residents.

Keywords: Urban Heat Islands, Urban Heat Island Evaluation, Urban Climatology, Heat Vulnerability, Urban Climate Planning

Introduction

By changing the reflectivity and energy balance of land, the built environment alters its climate and produces distinct microclimates (Gartland, 2008; Stone, 2012). The most problematic outcome of the built environment's influence is referred to as the Urban Heat Island effect (UHI). The UHI is defined as elevated urban air and surface temperatures relative to surrounding suburban and exurban areas (Solecki et al., 2005). Often expressed in terms of the degrees difference relative to cooler locations, areas with elevated UHIs increase residents' vulnerability to heat related illness and death, especially in summer (Gartland, 2008; Memon et al. 2007; O'Neill et al, 2005; Harlan et al., 2006). Research has found that in cities of the world the UHI increased air temperatures by 7 ^{o}C in London, United Kingdom (Wilby, 2003), 6.5 ^{o}C in Shanghi, China (Djen et al., 1994), and 12 ˚C in Lodz, Poland (Klysik & Fortuniak, 1999). While the UHI is a distinct phenomenon from global climate change, increasing temperatures and changing precipitation patterns are exacerbating its negative impacts (Stone, 2012). While UHIs can have some positive outcomes in wintertime (Oke, 1988; Santamouris et al., 2007), UHIs are largely problematic in warm weather. Fortunately, our knowledge of UHI patterns has advanced over the last forty years. We now understand that urban areas may contain many dispersed UHIs that change diurnally and are not limited to the urban core. In addition, UHI patterns depend on regional atmospheric transport, maritime influences, and land cover dynamics (Jenerette et al., 2007; Gaffin et al, 2008, Gray & Finster, 2000).

Ensuring safe, livable conditions in cities requires understanding where UHIs exist and how we can lessen their negative impacts during summer months. The cities of Albuquerque, Boise, Chicago, Hartford, Louisville, Minneapolis, New York, Philadelphia, Pittsburgh, and Portland currently have started UHI reduction programs (Stone, 2012). These programs generally seek to change the physical characteristics of neighborhoods based on UHI identification using measures of regional land cover derived from satellite images of surface temperatures. Improving our understanding of how the characteristics of land cover, neighborhood building configuration, and adjacent heat sources and sinks differentially contribute to urban climatology and meteorology will help urban planners determine the information they must collect to understand neighborhood microclimate variation so they can prioritize strategies to lessen the UHI negative effects. Although past research has looked at these physical characteristics separately, these three types have not been examined in combination. The value of this study is the examination of multiple potential factors to determine the ones that researchers and planners should prioritize.

Our study starts with a review of the urban climate literature to identify what are the most important factors relating to land cover, neighborhood building configuration, and adjacent heat sources and sinks that contribute to microclimatic variation. Then, I describe how I selected the eight Chicago Neighborhoods and measured their physical and heat characteristics. I then analyze this information to answer three questions. First, how do the factors of land cover, neighborhood building configuration, and adjacent heat sources and sinks differentially contribute to explaining elevated summer air temperatures in eight Chicago neighborhoods? Second, does the relative contribution of these factors vary between nighttime and daytime? Third, during heat events, does the relative contribution of the factors vary at night and during the day?

Literature Review

In this section I discuss 1) an overview of physical properties that create urban heat islands, 2) UHI/microclimate studies based on remotely sensed surface temperatures, 3) UHI/microclimate studies based on in-situ air temperatures, 4) the relationship between heat, humidity, and heat events, and 5) urban climate and built environment characteristics of Chicago.

Physical properties that create UHIs

The built environment impacts the albedo (reflectivity) and the emissivity (energy balance) of solar radiation. Taha (1997) estimated that, unlike natural areas, urban areas reflect only 15 -20% of the incoming shortwave radiation while absorbing and re-emitting 80-85% of that energy. Emissivity measures a material's ability to store heat energy and release it back into the atmosphere. Most concretes and asphalts have an emissivity around 0.90 (on a scale of 0 to 1.0), thus effectively storing and slowly releasing heat energy (Golden & Kaloush, 2006). In addition to generally being low albedo and high emissivity environments, urban areas have less available moisture than rural environments due to the prevalence of impervious pavements and buildings that replace natural vegetation and 'seal' soils. This undesirable sealing means that urban environments are drier and thus have a lower percentage of latent heat relative to sensible heat. Sensible heat directly warms the lower atmosphere by the process of convection and we can sense this type of heat. Conversely, we don't sense latent heat because it is transported in an undetectable form into the upper atmosphere as water vapor (Stone, 2012). Thus, latent heat does not contribute to UHIs. Therefore, reducing the UHI requires reducing the amount of undesirable sensible heat and increasing the presence of moisture that is a required to produce latent heat.

Another characteristic of urban environments that contributes to the UHI is the large percentage of impervious land cover relative to pervious land cover. Numerous broad-scale studies (derived from satellite images) have documented the relationship between impervious areas and higher surface temperature (Imhoff et al., 2010; Yuan & Bauer, 2007; Jenerette et al., 2007). For example, Imhoff and colleagues (2010) found that on average in 38 U.S. urban areas, 80% of urban core areas were covered by impervious surface. In the Chicago region, these researchers using satellite images found that the amount of impervious surface explained 89% of the variance in the surface temperature differences between urban and rural locations (Imhoff et al., 2010). Yuan & Bauer (2007) found the area of impervious surfaces explained 97% of the variance in surface temperatures during four seasons in the Minneapolis metropolitan area. Impervious surface was more important that the percentage of tree canopy. However, surface temperatures are only an indirect measure of air temperature.

Limitations of UHI/microclimate studies based on remotely sensed surface temperatures

The relationship between surface temperature and air temperature is mediated by factors such as surface roughness, wind speed, and wind direction (Stathopoulou & Cartalis, 2007: 359; Weng, 2009: 340, Weng & Quattrochi, 2006) and thus surface temperature measures omit these important factors. In Chicago, Coseo & Larsen (2012b) found that explanatory power of surface temperature to predict air temperature varied significantly by wind speed. During light winds (less than 1.21 m/s or 2.71 mph) the surface temperature explained 84.3% of the variance in air temperature. When wind speeds were higher (5.39 m/s or 12.06 mph), the explanatory power of surface temperature relative to air temperature decreased to explain 65.9% of the variance (Coseo & Larsen, 2012b). Angel (2012), the state climatologist for the state of Illinois, reports that during July and August Chicago's wind speeds have a 30 year average (1981-2010) of 13.2 km/h (8.2 mph) with a prominent wind direction of 240 degrees (west-southwest winds). Yet, winds are likely to vary by time of day with night receiving lighter winds due to decreased solar heating and less atmospheric mixing. While the day will have higher wind speeds associated with daytime heating of surfaces and increased mixing of the atmosphere. The imperfect relationship between surface temperature and air temperature will be of greater concern during the day when wind speeds tend to be higher than at night.

A second limitation of this technique is image resolution. While the resolution of satellite images varies, many studies use images that imply homogenous values for areas that range between 1000m down to 12 m in size (Voogt and Oke, 1998). This simplifies the complexity of the surface and contextual influences. Finally, a third significant limitation of using surface temperature derived from satellite images to predict air temperature is the reduction of a complex three-dimensional space into a two-dimensional plan. Akbari and colleagues (2003) found that in cities that have extensive tree canopies, such as Sacramento, the impervious area under tree canopies (that is neglected in two-dimensional analysis) increased the percentage of total impervious surface area from 64% to 81.55% in downtown Sacramento. After reviewing the limitations of using surface temperature information derived from satellite images, Voogt and Oke (2003) conclude that the limitations of surface temperature studies derived from broad-scale resolution satellite images make fine-grained, three dimensional in-situ air temperature investigations necessary.

UHI/microclimate studies based on in-situ air temperatures

In this next section I summarize urban climate studies that examine the impact of land cover, neighborhood building configuration, and adjacent heat sources and sinks on in-situ air temperature measured at a finer, microclimate scale. The term *land cover* is generally used to describe the relationship between impervious and pervious vegetated surfaces. As rural areas become urban, impervious surfaces replace pervious vegetated land covers. Dimoudi & Nikolopoulou, (2003) found that in Athens a 10% increase in the percentage of vegetated pervious cover to an impervious area decreased air temperature by 0.8^{0}C for urban areas where the building height to street width ratio was 1.5. In fact, the impact of impervious cover relative to pervious vegetated cover may change diurnally. Hamada & Ohta (2010) found that the percentage of tree canopy in Nagoya had a significant cooling effect explaining 72% of the variance in air temperature at 1:00 a.m. and 57% at 3:00 p.m. They found air temperature decreased by 0.34^{0}C at night (1 am) and by 0.43^{0}C in the afternoon (3:00 pm) for every 10% increase in tree canopy.

Vegetation contributes to cooling in highly impervious urban environments through evapotranspiration and shade (Dimoudi & Nikolopoulou, 2003; Shashua-Bar & Hoffman, 2000). Dimoudi & Nikolopoulou (2003) showed that in Athens, Greece as air temperatures approach 40^{0}C plants reduce their transpiration rates to avoid heat stress and evapotranspiration rates plummet. They found that tropical plants produced only slightly higher evapotranspiration rates than native plants that resulted in 0.5^{0}C of cooling and required more watering (Dimoudi & Nikolopoulou, 2003). Shashua-Bar & Hoffman (2000) examined small vegetated areas within Tel-Aviv and found that on average trees accounted for a 3.23 ^{0}C reduction in air temperatures. They estimated that 80% of this cooling was due to tree shading. While lawn areas are categorized as pervious, their ability to substantially reduce the UHI is much less than trees or woody shrubs. Stone & 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 sensible heat contribution to UHIs by 13% (Stone & Norman, 2006).

Three-dimensional neighborhood building configuration, specifically building height, building arrangement and street orientation impacts air temperature and may contribute to UHIs (Oke, 2004; Eliasson, 1996; Sakakibara, 1996). Oke (1987) has identified 2 layers critical for understanding urban climate: the *urban boundary layer* (UBL) and the *urban canopy layer* (UCL). The top of the UCL is determined by the building heights and continues down to the ground. Building heights determine the height of the UCL, solar access, shading, and radiational cooling. A more sophisticated measure of a neighborhood's three-dimensional space is the urban canyon ratio or the ratio of building heights to street widths (h/w). During the day, a larger h/w ratio means that more reflected solar radiation is captured by the building walls and thereby enhancing sensible heat. Sakakibara (1996) compared a wide (h/w = 0.71) east-west urban canyon with a narrow (h/w = 2.04) east-west oriented urban canyon and a parking lot in Tokyo, Japan. Sakakibara found that both canyons absorbed more daytime shortwave energy and released more sensible and longwave heat energy at night compared with the open parking lot. From an urban climate perspective, Oke (1988) suggests an ideal urban canyon ratio of between 0.40 to 0.60 (h/w). Oke and colleagues (1991) found that canyon geometry and the presence of impermeable surfaces were approximately equal in their contribution to the UHI formation.

Closely related to urban canyon is sky view factor (SVF). SVF is a way to measure the relative amount of obstructed sky or openness at a particular location. SVF varies from 0 - 1.0, where 1.0 is 100% unobstructed sky, such as an open parking lot without trees. SVF has been found to be an important measure of the potential of a location for radiational cooling (Eliasson, 1996; Svensson, 2004). In fact, Chang and colleagues (2007) found that parks with more than 40% lawn areas were actually cooler at night in summer than those with less lawn and more trees because tree canopies reduced radiational cooling. Low values of SVF may have the effect of keeping some areas warmer as dense tree canopies slow the heat dissipation during nighttime hours (McPherson et al., 1997).

Orientation of streets affects shading and air circulation, thus influencing air temperature and UHIs. Ali-Toudert & Mayer (2007) found that east-west oriented streets in Ghardaia, Algeria had the highest temperatures even in deep canyons (h/w ratio of 4) due to the lack of shading over the course of the day. In the same study, wind flow simulating a 5 m/s breeze perpendicular to street orientation decreased wind speeds at ground level to 0.3 m/s within the urban canyon (Ali-Toudert & Mayer, 2007). By simulating a wind of 5 m/s that was parallel to the street orientation, these researchers were able to reduce the air temperature by 12^0C for the same urban canyon ratio (Ali-Toudert & Mayer, 2007).

Finally, a less studied area of UHI research concerns upwind adjacent heat sources and sinks. Heat sources and sinks from areas adjacent to the neighborhood may impact air temperature as winds transport air from upwind locations. An upwind area's temperature footprint is heavily dependent on the adjacent area's physical characteristics, atmospheric stability, surface roughness, wind direction and speed, as well as the height of the weather sensor (Kljun et al., 2004; Voogt & Oke, 2003; Oke, 2004). Oke (2004) provides a general guide that the source area footprint of a sensor placed at three m. height extends in an elliptical shape up to 0.5 km upwind from the sensor. Upwind heat sources may play an important role in contributing anthropogenic waste heat to certain neighborhood microclimates (Britta & Hanna, 2003; Fan & Sailor, 2005; Shashua-Bar & Hoffman, 2000). Shashua-Bar & Hoffman (2000) found waste heat from vehicles accounted for up to 2^0 C of warming in heavily trafficked neighborhoods Tel-Aviv. Some research has indicated that anthropogenic heat, such as waste heat from industry, cars, and air conditioning units, increases UHIs by 1 to 5^0 C (Fan & Sailor, 2005; Shashua-Bar & Hoffman, 2000). However, large vegetated areas or bodies of water may also act as heat sinks, decreasing air temperatures in downwind neighborhoods. Trying to measure the impact of large water bodies on air temperature, Memon & Leung (2010) found that wind speed explained 80% of the variance in air temperature in Hong Kong. As mean wind speed increased by +1.0 m/s in Hong Kong's maritime environment, air temperature cooled by 1.9^{0}C (Memon & Leung, 2010). Saaroni and colleagues (2000) found that in Tel-Aviv sea breezes were more likely to penetrate and cool areas of the city with a more open character such as plazas, wide roads, and large intersections.

Within the urban climate literature, the characteristics of land cover, neighborhood building configuration, and adjacent heat sources and sinks have been found to alter local air temperatures. Yet, past studies have not examined the relative contribution between the three categories of physical drivers and UHI formation. Understanding the relative contribution between these three factors and how they contribute to elevated air temperature at different times of day and during heat events is critical in advancing our strategic manipulation of site-level characteristics to reduce undesirable UHI effects.

Heat, humidity, and heat events

UHIs amplify heat events causing residents' living in UHI areas to experience increased heat exposure (Stone, 2012). Extreme heat events are days that the maximum apparent temperature (how the combination of heat and humidity feel) exceeds the 85th percentile of average long-term temperatures (Sheridan et al., 2009; Stone et al., 2010; Gaffen & Ross, 1998). Two times of day are critical times of exposure during heat events: nighttime (1 to 2 a.m.) and late afternoon when maximum temperatures occur (4 to 5 p.m.) (Solecki et al, 2005). Although nights are cooler than days, during heat events nighttime air temperatures might not fall low enough to provide residents with sufficient relief. Heat at night can prevent proper rest, create physiological stress for residents, and is the greatest predictor of heat-related mortality (Kalkstein & Davis, 1989). Although air conditioning may serve as a mechanism to cope with high temperatures, not all residents benefit from air conditioning (O'Neill et al., 2005). Due to the dangers of heat, Sheridan (2012) has developed a system to classify days when extreme heat has raised the risk of heat related illness. Sheridan's (2012) *Spatial Synoptic Classification System* classifies days when extreme heat or the combination of heat and humidity raise the risks of heat related illness. Sheridan's (2012) system differs from National Weather Service heat warning system in that it classifies days as dangerous based on four daily readings of air temperature, dew point, wind, pressure, and cloud cover. It accounts for more variables than the NWS heat index, which relies on only air temperature and humidity. The NWS (2009) classification system is based only on shade and light wind conditions. The NWS (2009) warn that heat indices may be as much as 15°F warmer in sun and stronger winds. This makes Sheridan's (2012) system a more sophisticated method to classify potentially dangerous days.

Nighttime is not only the time when heat mortality is most important (Kalkstein & Davis, 1989), but it is also the time when UHIs or the difference between urban and rural air temperatures is the highest. UHIs intensify at night in the presence of clear skies and light winds when heat energy stored in urban materials is more efficient at heating the UCL (Djen et al, 1994: 2126; Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999; McPherson et al., 1997). In Chicago, maximum daytime UHIs often move toward the western suburbs because of the Lake breeze. However, at night the winds generally reverse to bring higher temperatures back toward downtown overnight (Gray & Finster, 2000). This is particularly troubling since Stone (2012: 78) found that during one Chicago heat wave from in July 1999, the UHI intensity increased from 2-3^{0} F before the heat wave to greater than 6 ^{0}F during the heat wave. Not only were urban centers hotter on an average basis, but during heat waves the UHI intensity was amplified. Only a limited number of UHI studies have examined the relationship between physical characteristics and UHIs at different times of day (Hamada & Ohta, 2010; Zhang et al., 2011)

Finally, past research found that UHIs align with income, placing lower income residents are higher risk of heat exposure and illness (Jenerette et al., 2007; Santamouris et al., 2007; Solecki, et al., 2005). These studies point to the importance of vegetation in buffering residents from heat exposure. Several studies have found that the presence of vegetation aligns with income resulting in poorer neighborhoods being disproportionately exposed to higher UHIs (Jenerette et al., 2007; Santamouris et al., 2007; Solecki, et al., 2005). Jenerette and colleagues (2007) found that, at 10 a.m. on a May morning, for every $10,000 decrease in neighborhood annual median household income in Phoenix neighborhoods was associated with a 0.28^{0}C increase in the surface temperature. Poorer residents likely could not afford the extra expense of vegetation and irrigation required to maintain healthy vegetation (Jenerette et al., 2007). Solecki and colleagues (2005) found that poorer neighborhoods in New Jersey had more impervious surfaces and less private yard space to plant vegetation. Yet, the finding that UHI intensity aligns with income has only been investigated in a few cities (Phoenix, Athens, Newark and Camden, New Jersey). Researchers have not adequately addressed this pattern in other regions where vegetation may not necessary align with income.

Chicago's urban climate

The Chicago region lies at the southeast corner of the Lake Michigan on a flat lake plain (41^0 52' 55" North and 087^0 37' 40" West ($USGS_a$, 2012)) with minimal elevation changes of 176.5 m (579 ft.) to 205.1 m (673 ft.) above sea level ($USGS_b$, 2012). Generally, Chicago has a moderate continental climate of warm humid summers and cold snowy winters with an average mean temperature from May to September of 25.9^0C (1961-1990) (Hayhoe et al., 2010_a). In July and August, prevailing west-southwest (240^0) winds average of 13.2 km/h (8.2 mph) (1981-2010) transporting in warm humid air from the central and southern plains (Angel, 2012). The highest recorded temperature in Chicago was 40.6^0 C (105^0F) on July 24, 1934 and the lowest recorded temperature of -32.8^0C (-27^0F) was recorded on January 20, 1985 (NWS Chicago Records, 2012). In 2012, Chicago had three record highs above 37.8^0C (100^0F) approaching the July 24, 1934 record (July 4, 38.9^0C (102^0F), July 5, 39.4^0C (103^0F), and July 6, 39.4^0C (103^0F)) (NWS, 2013). Tree cover plays an important role in moderating air temperatures in the region. A study by McPherson and colleagues (1997) found that the city of Chicago had an average tree canopy of 11%. Street trees comprised 10% of the total canopy in the city, but contributed 24% of the total leaf surface area for all trees in Chicago. While the 2010 population of the Chicago-Joliet-Naperville metropolitan statistical was 9,461,105, the population of Chicago was 2,695,598 residents (US Census, 2012). In 2010, Chicago had an average density of 4,572.2 persons per square km or 45.7 persons per hectare (11,841.8 persons per square mile or 18.5 persons per acre) within the City limits. Current regional UHI patterns are likely to intensify with a warming climate and further urbanization in the region.

Research Questions

This study examines how the physical characteristics of eight neighborhoods in Chicago differentially contribute to elevated air temperatures. Specifically I investigate three research questions. First, how do the physical characteristics of land cover, neighborhood configuration, and adjacent heat sources and sinks contribute to elevated summer air temperatures in eight Chicago neighborhoods? Second, do the relative contribution of the factors vary in importance between nighttime and daytime? Finally, the third research question investigates whether the factors that explain nighttime and daytime UHIs shift in importance during a heat event. Based on the urban microclimate literature, I expect, that fine-grained measures of percent impervious and the percent tree canopy will be the most important influence on microclimate temperatures for both night and daytime. However, based on the diurnal variation in wind speed, I hypothesize that neighborhood building configuration variables of urban canyon and orientation will be important in explaining nighttime temperatures while adjacent heat sources and sinks will be more important during the daytime when wind speeds are greater.

Methods

Study neighborhoods

We used three criteria to select the eight Chicago neighborhoods. I selected neighborhoods near documented UHIs that represented high, middle, and lower income neighborhoods with racial variation. First, I used a city of Chicago (2006) study of elevated surface temperatures to select neighborhoods within 1,000 feet of an elevated surface temperature area. Second, I selected lower (less than $26,405), middle (between $26,406 and $52,809), and high (greater than $ 52,810) income neighborhoods based on 2000 U.S. Census block group data and a study from the De Paul Institute for Housing Studies (IHS, 2009). Finally, I examined the racial composition of this neighborhood subset in the three income levels to select neighborhoods that varied in racial mix based on 2000 U.S. Census block group data. The selected neighborhoods were Belmont Cragin, Logan Square, Austin, Wicker Park, Little Italy, Bronzeville, Beverly, and East Side (figure 3.1). The neighborhood of Beverly was not near an UHI area but was included in the neighborhood selection because it represented an example of a neighborhood with lower impervious cover, higher tree canopy and added another location in the SW portion of the city. Within each of the selected neighborhoods I selected one representative city block in which to take air temperature, relative humidity, and to calculate the physical characteristics. The study was conducted with four east-west oriented alleys (Beverly, Austin, Little Italy, and Wicker Park) and four neighborhoods with north-south oriented alleys (East Side, Bronzeville, Belmont Cragin, and Logan Square) to understand how orientation may influence canyon shading and ventilation and thus contribute to air temperatures.

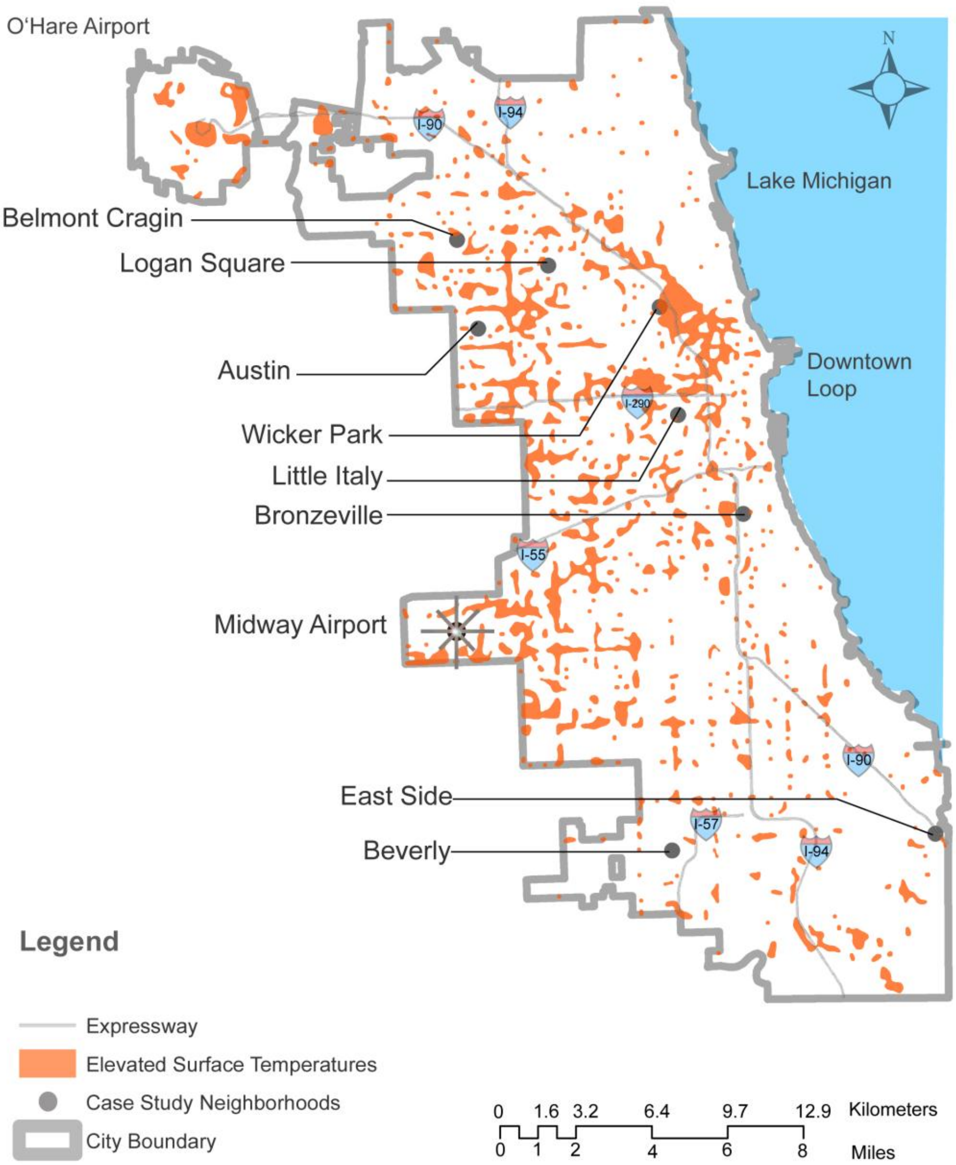

Figure 3.1: Map illustrating the city of Chicago limits, the eight study neighborhood, Midway Airport, and the heterogeneous distribution of elevated surface temperatures from a City of Chicago Department of the Environment 2006 study.
Data source: City of Chicago Department of Environment GIS database, accessed February 1, 2010
Illustration: by authors

Social Characteristics in 2010

Although I selected neighborhoods with 2000 block group level data, I conducted the research in 2010 and report 2010 census tract data. Table 3.1 and 3.2 describe each neighborhood's social and physical characteristics ordered from highest 2010 census tract median household income to lowest median household income. Median household income in 2010 was lowest in the neighborhoods of Bronzeville, Austin, and East Side falling below $40,000 annually. Middle-income neighborhoods include Belmont Cragin, Little Italy, and Logan Square. Beverly and Wicker Park were classified as high income neighborhoods with 2010 median household incomes of $50,000 or more. The ethnic and racial makeup of the neighborhoods varied among the eight neighborhoods. In Little Italy, 33.5% of residents identified themselves as Non-White while in Austin 96.8% of residents identified themselves as Non-White in 2010. In 2010, population density varied from a low of 30.0 people per hectare (12.1 people per acre) in Beverly to a high of 94.8 people per hectare (38.4 people per acre) in Wicker Park.

Table 3.1: Descriptive Statistics of Neighborhood Social, Density, and Land Cover Characteristics for Eight Chicago Neighborhoods in 2010

	Social * Characteristics		Density*				Land Cover**		
Neighborhood	Median Household Income	% Non-White	Density Units / Hectare (per acre)		Density People / Hectare (per acre)		% Impervious Surfaces	% Roof Cover	% Tree Canopy
Wicker Park	$84,205	21.7	47.4	(19.2)	94.8	(38.4)	95.7	34	4.7
Beverly	$56,346	66.3	14.3	(5.8)	30.0	(12.1)	54.6	22.9	60.4
Logan Square	$43,116	48.8	27.0	(10.9)	70.6	(28.6)	88.1	37.9	13.2
Little Italy	$42,663	33.5	30.9	(12.5)	55.1	(22.3)	94.3	39.1	29.4
Belmont Cragin	$40,528	44.9	26.0	(10.5)	83.5	(33.8)	78	37.9	18.1
East Side	$38,032	46.3	19.2	(7.8)	56.8	(23.0)	73.5	31.9	23.1
Austin	$31,263	96.8	35.3	(14.3)	92.0	(37.2)	75.1	28.2	19.7
Bronzeville	$19,316	88.9	35.7	(14.4)	58.9	(23.8)	79.9	21.8	18.5

* Social Characteristics and Densities are from 2010 U.S. Census Tract data
** Calculated by authors from April 9, 2010 USGS orthoimagery.

Table 3.2: Descriptive Statistics of Building Configuration and Adjacent Heat Sources and Sinks for Eight Chicago Neighborhoods in 2010

	Neighborhood Building Configuration**				Adjacent Heat Sources and Sinks**						
Neighborhood	Urban Canyon Ratio	Average Build Heights on Block (m)	Sky View Factor	Alley Orientation	% Tree Canopy Upwind Area	Average Build Heights in Upwind Area (m)	Distance to Lake (km)	Distance to Down-town (km)	Distance to Industrial (km)	Distance to Freeway (km)	Distance to Park (km)
Wicker Park	0.78	13.8	0.53	E-W	11.0	14.3	3.6	3.3	2.6	4.8	4.4
Beverly	0.24	9.1	0.51	E-W	49.5	9.1	11.5	19.2	5.9	7.5	2.7
Logan Square	0.44	12.4	0.66	N-S	8.3	12.2	8.0	8.3	0.2	8.1	11.5
Little Italy	0.6	13	0.49	E-W	30.0	15.2	3.7	2.1	1.7	7.3	9.2
Belmont Cragin	0.32	10.4	0.67	N-S	12.7	10.4	11.6	12.4	1.4	9	1
East Side	0.29	9.9	0.69	N-S	18.1	9.8	0.4	20.3	1.9	7.1	1.5
Austin	0.31	10.8	0.7	E-W	23.3	10.7	11.4	10.5	2.1	4.5	6.5
Bronzeville	0.28	9.1	0.65	N-S	14.0	10.7	1.4	4.6	1.6	1.1	9.1

** Calculated by authors from April 9, 2010 USGS orthoimagery.
Alley orientation (north-south or east-west)
Distance from each block to Lake Michigan is a straight line (not in upwind direction)
Distance from each block to Downtown (Loop) is a straight line (not in upwind direction)
Distance from each block to upwind (southwest) industrial areas, freeways, and large parks is a straight line

Neighborhood physical characteristics

The eight neighborhoods varied in compactness with the density of units per hectare in 2010 ranging from a low of 14.3 units per hectare (5.8 units per acre) in Beverly to a high of 47.4 units per hectare (19.2 units per acre) in Wicker Park. Beverly had the lowest amount of impervious surface with 54.6 %, while Wicker Park had the highest with 95.7%. Similarly Beverly had the highest tree canopy with 60.4% coverage and Wicker Park the lowest with 4.7% coverage. Yet, the amount of tree canopy was not an inverse relationship with the amount of impervious surface area. Wicker Park and Little Italy both had roughly 95% impervious surface areas, but while Wicker Park had less than 5% tree canopy Little Italy had nearly 30% tree canopy. The urban canyon ratio was lowest in Beverly with a h/w ratio of 0.24 and greatest in Wicker Park with a h/w ratio of 0.78. The neighborhoods' distance from Lake Michigan ranged from 0.43 km (0.27 miles) for East Side to more than 11 km (7 miles) for Belmont Cragin.

Weather observation instruments

We took weather observations using stationary Onset U23-002 HOBO External Temperature/RH Data Logger with sensor and a model RS3 solar radiation shield. The HOBO weather stations have an air temperature accuracy of ±0.2^{0}C from 0 to 50^{0}C and relative humidity accuracy of ±2.5% from 10 to 90% relative humidity (Onset, 2010). Additional hourly weather observations from July 1 to August 31, 2010 were obtained from Midway Airport located in the city of Chicago (figure 3.2). Data from this location is used to calculate baseline air temperature, relative humidity, wind speed and direction, and sky condition. Past UHI studies in the Chicago region have used O'Hare (McPherson et al., 1997) while other more recent studies have used multiple urban and suburban sites within the Chicago region (Gray & Finster, 2000). For this study I used Midway Airport (figure 3.4) and not O'Hare Airport because the predominate wind direction was out of the southwest direction (210 degrees) during the study period, so Midway (due to its more southwesterly location) provides a better comparison before air masses move over the urban neighborhoods. Although Midway is well with the Chicago urbanized region the airport's open character allows for ventilation and mixing of the air. In addition, the weather station is located at the center of the tarmac (see figure 3.5) west of the terminal and away from idling jets. Finally, although impervious surfaces cover roughly 61% of the airport grounds, as calculated from aerial orthoimages, the runways are lighter colored concrete that would absorb less solar radiation than asphalt.

Two other weather stations were considered to measure base weather conditions, a suburban station in Romeoville, IL (figure 3.3) and a rural station in Sugar Grove, IL (figure 3.4) were considered for the analysis. First, Romeoville was surrounded by low density suburban development and at least 45 km southwest of Chicago's downtown Loop (figure 3.2). In addition, the Romeoville site was missing some data from a few days. Romeoville was not used for surrounding urbanization, distance from the eight neighborhoods, and missing data. For Sugar Grove, although it was the closest rural weather station to the west of the neighborhoods it was at least 70 km from the downtown Loop area. Sugar Grove was not used because of the extreme distance from both the urban core and Lake Michigan. In addition, the Fox River Valley results in topographical changes between Sugar Grove and the eight neighborhoods, which may have influenced air temperatures.

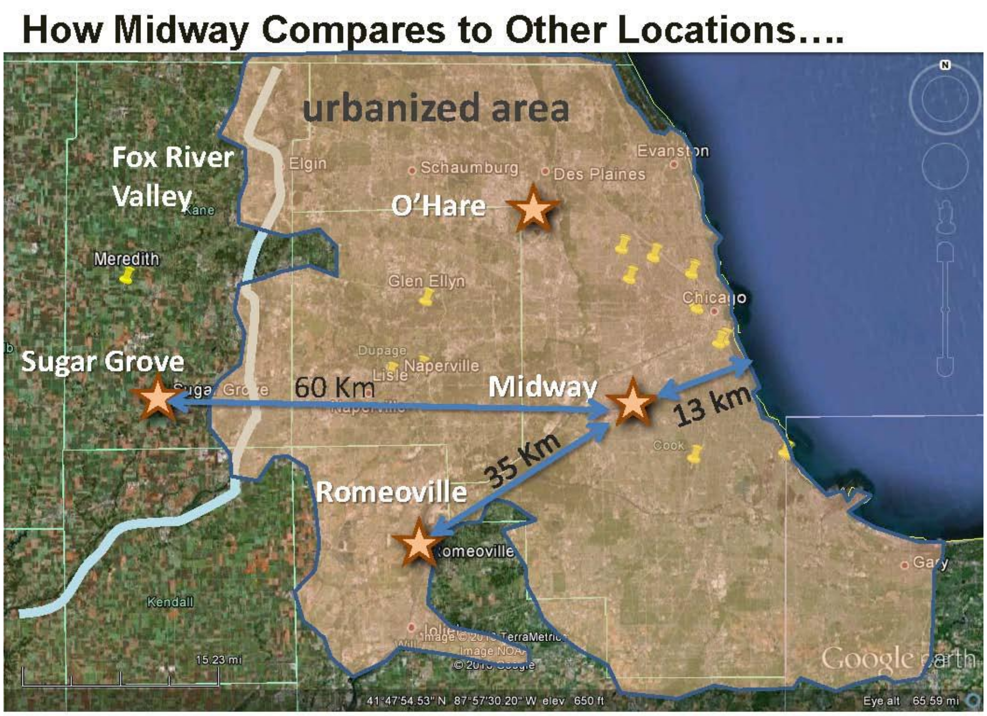

Image Source: Google Earth

Figure 3.2: Midway Airport relative to other regional weather stations located at Sugar Grove (KARR) and Romeoville (KLOT), not to scale
Photograph: Google Earth
Illustration: by author

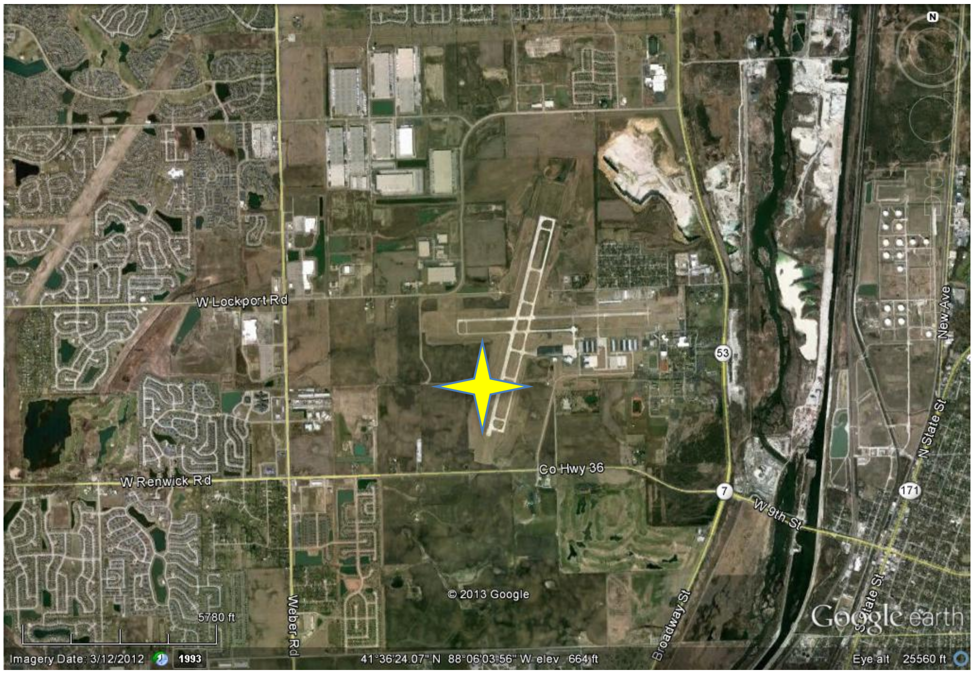

Figure 3.3: Location of Romeoville (KLOT) weather station (indicated by star) as documented by http://weather.gladstonefamily.net/site/KLOT, accessed December 30, 2012, not to scale
Photograph: Google Earth

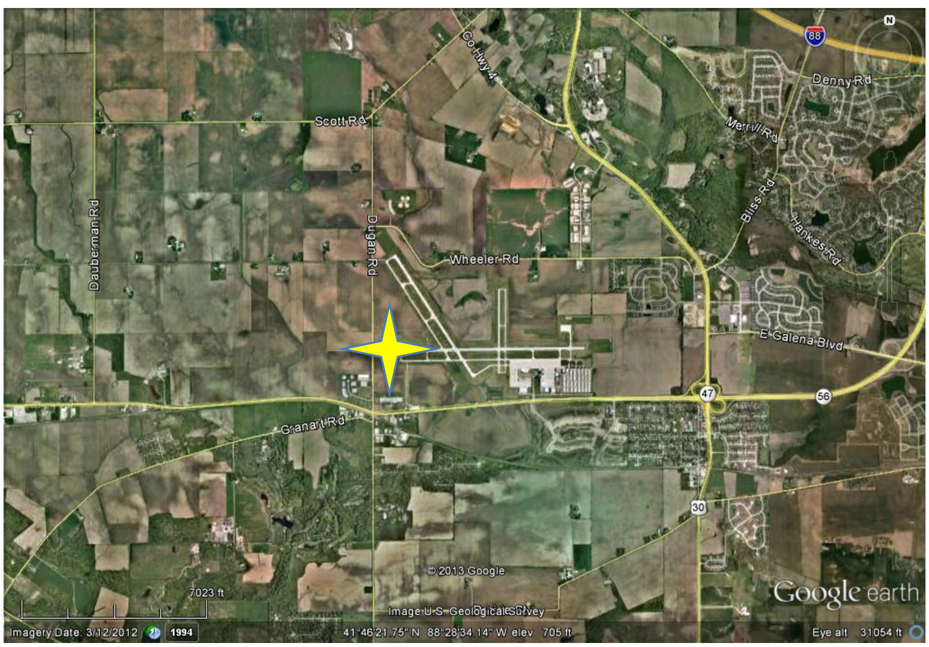

Figure 3.4: Location of Sugar Grove (KARR) weather station (indicated by star) as documented by http://weather.gladstonefamily.net/site/KARR, accessed December 30, 2012, not to scale
Photograph: Google Earth

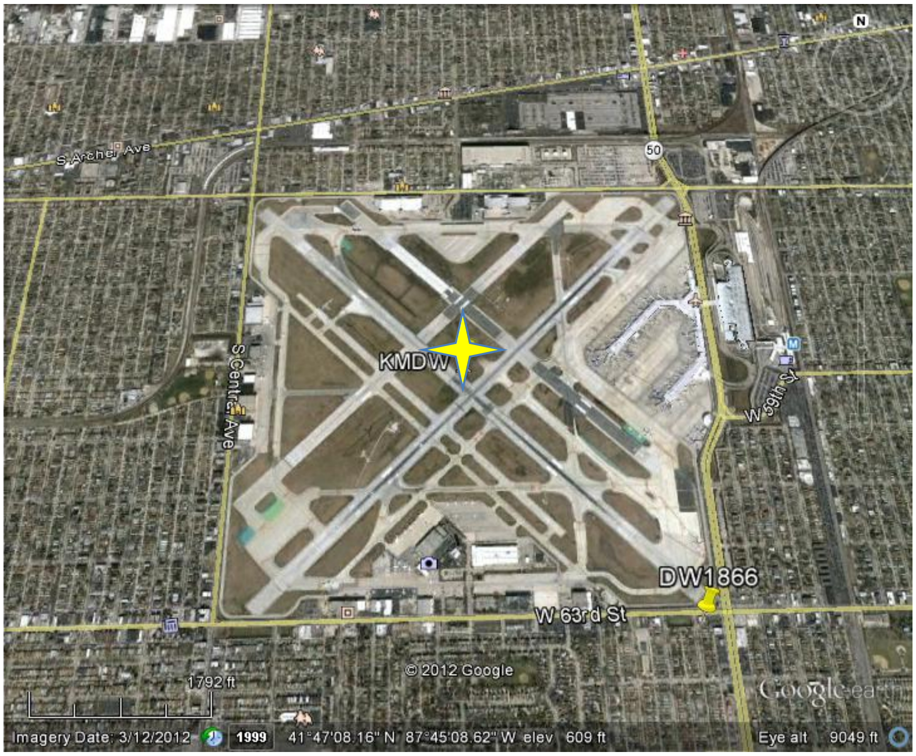

Figure 3.5: Location of Midway Airport (KMDW) weather station (indicated by star) as documented by http://weather.gladstonefamily.net/site/KMDW, accessed December 30, 2012, not to scale
Photograph: Google Earth

Data collection procedures:

In locating the HOBO units, I used the *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites* criteria (Oke, 2004) to establish the locations and heights of the equipment. Each HOBO unit was mounted on the north or east side of a utility pole at a height of three meters (above the height of truck traffic) at the center of each neighborhood block's alley collecting ambient air temperature and relative humidity every 5 minutes for 24 hours a day from July 1 to August 31, 2010. The placement was within the urban canopy layer as residential building heights were at minimum 9.14 meters. The solar radiation shield was mounted to the utility pole with two screws and two zip ties to secure the station and the data logger with the logger window facing upwards. Data were downloaded every two weeks using a HOBO data shuttle to transfer the data from each weather station to a laptop computer. I chose two important times during the day to focus on for the analysis. I used the time of 2 a.m. in the analysis because past research (Kalkstein & Davis, 1989) has pointed to the importance of cooling relief at night for human well-being. I also selected 4 p.m. because it was the statistical average time for maximum daily highs over the two-month period. The UHI intensity or the difference in air temperature (ΔT_{air}) between the eight neighborhoods and Midway Airport was calculated for both 2 a.m. and 4 p.m. ΔT_{air} at 2 a.m. and 4 p.m. serves as the dependent variable in the analysis.

Quantifying neighborhood physical characteristics

We quantified 15 independent variables for the study including density, land cover, neighborhood building configuration, and adjacent heat sources and sink variables (Tables 3.1 and 3.2). Density of units per acre was obtained from 2010 census tract data for each neighborhood. USGS high resolution orthoimagery from April 9, 2010 was used to calculate all land cover percentages including impervious surfaces, roof cover, and tree canopy (http://earthexplorer.usgs.gov/). Using a similar method to Akbari and colleagues (2003), three-dimensional impervious surface was calculated by hand in AutoCAD (an architectural drafting program) as the percentage of the whole block including a portion of the street's impervious surface extended out from street curb to mid street. Only deciduous shade and coniferous trees were included in calculations for tree canopy. The urban canyon ratio was calculated as the average height of the block's buildings to the width of the alley and backyard space at each collection location.

Neighborhood building configuration variables were building heights, urban canyon ratio, SVF, and urban canyon orientation. Average building heights and urban canyon ratio for each block were estimated by using aerial orthoimagery, site visits, and the Chicago Zoning Code Summary of standard building heights for each neighborhoods building type (Chicago Zoning Code, 2012). Sky view factors (SVF) were calculated at ground level below each weather station similar to Svensson (2004) using a Solmetric SunEye. Orientation of the urban canyon was calculated as a dummy variable, either 0 for north-south oriented alleys or 1 for east-west oriented alleys. The UHI intensity or the difference in temperature between each neighborhood and Midway was calculated for 2 a.m. and 4 p.m. for 12 clear days in July and August, 2010. For the ellipse of adjacent heat sources and sinks I calculated both percentage of tree canopy (heat sink) and average building heights (heat source) for a 0.5 km long elliptical source area to the southwest (upwind) of each HOBO weather station. Finally, I quantified the distances from the neighborhood to Lake Michigan, downtown Chicago Loop, and other potential heat sources and sinks to the southwest (upwind) of each neighborhood.

Results

Although not an extreme summer in terms of the number of heat events, the summer of 2010 was consistently warm. To begin, I explored the effect of controlling for heat event days, clear skies, and heat event days with clear skies to understand how this affected UHI intensity (ΔT_{air}). Table 3.3 describes four different types of UHI intensity or ΔT_{air} analysis between the neighborhoods and Midway Airport during July and August 2010 using data from 1) all 62 days, 2) 12 heat event days with or without cloud cover only, 3) 12 clear days only, and 4) two clear heat event days only. First, to select the 12 heat event days (clear and cloudy) I used Sheridan's (2012) Spatial Synoptic Classification System to identify days when the combination of heat and humidity pose a dangerous threat to residents. Then, to isolate urban factors that contributed to the warming (UHI) in the eight neighborhoods, I selected only days with clear skies with light winds (24 hours of clear skies and relatively light winds) as recommended by urban climate researchers (Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999; McPherson et al., 1997). This reduced the number of days I analyzed from 62 days to 12 clear days. Finally, of the 12 clear days I selected the only two clear days, to again isolate the urban-induced warming.

Generally controlling for clear skies raises the average UHI intensity for all neighborhoods by +0.11°C (+0.21°F) at 2 a.m. and +0.42°C (+0.76°F) from all 62 days. Although this is not much, at 2 a.m. the range in UHI intensities (ΔT_{air}) increases from 2.97°C (5.35° F) during all 62 days to 4.15°C (7.88°F) during the 12 clear days. At night, controlling for weather (clear skies) resulted in Beverly with more intense cool island conditions (lower air temperature than Midway) and Wicker Park with more intense UHI conditions. During the day the change in the range of UHI intensities is not as large (from 2.28°C (4.11°F) for all 62 days to 2.85°C (5.13°F) for the 12 clear days). This finding suggests the benefits of controlling for weather to isolate urban-induced warming from other warming effects.

To put Midway in perspective, in relation to other regional locations during these 12 clear days, Midway Airport was consistently warmer than Romeoville, IL (suburban site) and Sugar Grove, IL (rural site). The largest differences in air temperature (ΔT_{air}) were at night during the 12 clear days. At 2 a.m. Midway Airport was on average 3.01^0C ±0.81 (n=11) warmer than Romeoville and 4.39^0C ±0.93 (n=12) warmer than Sugar Grove. During the afternoon the difference was not as great. At 4 p.m. Midway Airport was roughly on average the same as Romeoville, with air temperatures $+0.01^0$C ±0.94 (n=11) warmer than Romeoville and 0.51^0C ±0.92 (n=12) warmer than Sugar Grove. One of the 12 clear days at Romeoville had missing data, which brought the number of days for analysis to 11. The distance to both Romeoville and Sugar Grove and lack of data in Romeoville (suburban site) led us to use Midway Airport to calculate the difference in air temperatures.

As for the neighborhoods compared to Midway (ΔT_{air}), for the 12 clear days, the warmest neighborhood at night was Wicker Park averaging $+2.34^0$ C ±0.73 (4.21^0F ±1.31) warmer than Midway airport. The coolest neighborhood was Beverly, with average air temperatures -1.81^0C ± 0.85 (-3.26^0F ± 1.55) cooler than Midway Airport. During the day the ordering of the warmest to coolest neighborhoods shifted. Belmont Cragin unseated Wicker Park as the warmest neighborhood during the late afternoon (with average readings $+2.68^0$C ±0.59 (4.83 ^{0}F ±1.06) warmer than Midway). At 4 p.m. in the afternoon, Beverly still ranked as the coolest neighborhood. The accuracy of the HOBO weather stations was $\pm0.20^0$C. Finally, through ANOVA analysis I found that there was a statistically significant difference between neighborhoods air temperature at both 2 a.m. ($F = 28.91$, df = 7,88) and 4 p.m. ($F = 6.04$, df = 7,88) at the 0.001 level.

Our results show that the warmest neighborhoods during the 12 clear days (Wicker Park at 2 a.m. and Belmont Cragin at 4 p.m.) were not the poorest neighborhoods. In this small sample of eight neighborhoods there was no correlation between elevated air temperature and median household income contrary to previous studies that link low amounts of vegetation and low income to hotter neighborhoods (Jenerette et al., 2007; Santamouris et al., 2007; Harlan et al., 2006; Solecki et al., 2005). The lowest income neighborhood (Bronzeville with a median household income in 2010 of $19,316) had 18.5% tree canopy. Whereas higher income neighborhoods such as Wicker Park and Logan Square with household incomes in 2010 of $84,205 and $43,116 respectively had lower percentages of tree canopy (Wicker Park 4.7% and

Logan Square 13.2% tree canopy). In addition, both Wicker Park and Logan Square were consistently warmer than Bronzeville at 2 a.m. and 4 p.m.

Table 3.3

Air Temperature Difference from Midway Airport during July and August 2010

2 a.m.	All Days (n=62) Temperature Differences		12 Heat Event Days* (n=12)		12 Clear Days* UHI (n=12)		2 Clear Days* Heat Events** UHI (n=2)	
Neighborhood	C	F	C	F	C	F	C	F
Beverly	-1.04	-1.88	-0.86	-1.54	-1.81	-3.26	-1.86	-3.34
East Side	0.35	0.62	-0.06	-0.11	0.41	0.74	0.39	0.7
Belmont Cragin	0.75	1.34	0.91	1.64	0.74	1.34	1.53	2.75
Austin	0.83	1.49	0.93	1.67	0.84	1.51	1.38	2.48
Bronzeville	0.99	1.78	0.56	1.01	1.41	2.54	1.52	2.73
Logan Square	1.41	2.54	1.28	2.31	1.73	3.12	1.97	3.55
Little Italy	1.67	3	1.29	2.33	2.06	3.71	2.18	3.92
Wicker Park	1.93	3.47	1.59	2.86	2.34	4.21	2.52	4.54
Total	0.86	1.55	0.71	1.27	0.97	1.74	1.2	2.16

4 p.m.	All Days (n=62) Temperature Differences		12 Heat Event Days* (n=12)		12 Clear Days* UHI (n=12)		2 Clear Days* Heat Events** UHI (n=2)	
Neighborhood	C	F	C	F	C	F	C	F
Beverly	-0.06	-0.12	-0.68	-1.22	-0.17	-0.3	-0.95	-1.71
Bronzeville	0.9	1.61	1.12	2.01	1.76	3.17	1.4	2.52
East Side	0.94	1.69	1.28	2.30	1.76	3.17	0.85	1.53
Wicker Park	1	1.81	1.27	2.28	1.33	2.39	1.1	1.98
Little Italy	1.01	1.83	1.27	2.28	1.57	2.82	1.75	3.15
Austin	1.59	2.86	1.51	2.72	1.82	3.27	2.15	3.87
Logan Square	2	3.6	1.93	3.48	2.23	4.01	2.3	4.14
Belmont Cragin	2.22	3.99	2.27	4.08	2.68	4.83	3.3	5.94
Total	1.2	2.16	1.24	2.24	1.62	2.92	1.49	2.68

* Heat Event days as derived from Sheridan's (2012) Spatial Synoptic Classification system calculated at O'Hare Airport

**Clear days are days with 24 hourly Midway Airport sky conditions reported as clear, mostly clear, or partly cloudy

***Heat event days with clear skies only derived from Midway Airport sky condition observations and Sheridan's (2012) Spatial Synoptic Classification system calculated at O'Hare Airport

Positive numbers indicate warmer conditions in degrees (C = Celsius, F = Fahrenheit).

In the first analysis, I conducted a bivariate analysis to understand the relationship between each independent variable and the 2 a.m. and 4 p.m. ΔT_{air} neighborhood air temperatures difference controlling for weather (12 clear days) (table 3.4). At 2 a.m. during the 12 clear days the 11 significant bivariate correlations (p=.01) were 1) percent impervious surface (.82), 2) percent tree canopy (-.72), 3) distance to downtown (-.70), 4) upwind building heights (.67), 5) upwind industrial (-.65), 6) building heights (.63), 7) upwind tree area (-.62), 8) urban canyon ratio (.60), 9) percent of roof (.47), 10) upwind vegetation (.46), and 11) distance to lake (-.40). At 4 p.m. during the 12 clear days the seven significant bivariate correlations (p=.01) were 1) upwind industrial (-.52), 2) upwind trees (-.48), 3) percent tree canopy (-.44), 4) SVF (.38), 5) orientation (-.36), 6) percent roof area (.33), and 7) percent impervious (.30). In general, both the number of independent variables and strength of the bivariate relationships between the independent variables and ΔT_{air} were greater at 2 a.m. than at 4 pm.

Table 3.4: Bivariate Correlations between Physical Characteristics and the UHI intensity at 2 a.m. and 4 p.m. for eight Chicago neighborhoods during 12 clear days in summer 2010

	UHI Intensity		**Land Cover**			**Neighborhood Configuration**				**Adjacent Heat Sources and Sinks**						
	2 am	4 pm	% ISA[+]	% Roof	% Tree Canopy	UC[++] ratio	Build Ht. of Block	SVF	Orien. (0, 1)	% Tree Canopy in Source Area	Build Ht. of Source Area	Dist. to Lake	Dist. To down-town	Dist. To Indust	Dist. To Fwys.	Dist. To Parks
Neighborhood	-.23*	-.10	-.19	.20*	.08	.01	.11	.07	-.18	-.03	-.21*	.09	.55**	.11	.55**	-.22*
UHI Intensity 2 am		.19	.82**	.47**	-.72**	.60**	.63**	.03	-.07	-.62**	.67**	-.40**	-.70**	-.65**	-.22*	.46**
UHI Intensity 4 pm			.30**	.33**	-.44**	.03	.12	.38**	-.36**	-.48**	.08	-.04	-.17	-.52**	.04	.10
% Impervious				.67**	-.78**	.83**	.85**	-.14	.00	-.66**	.89**	-.45**	-.84**	-.70**	-.12	.51**
% Roof					-.46**	.55**	.72**	-.05	-.10	-.43**	.60**	.01	-.30**	-.59**	.64**	.10
% Tree Canopy						-.49**	-.53**	-.43**	.33**	.95**	-.44**	.35**	.55**	.81**	.27**	-.26*
Urban Canyon							.94**	-.55**	.42**	-.30**	.92**	-.31**	-.70**	-.21*	-.00	.24*
Building Ht. of Block								-.39**	.37**	-.36**	.91**	-.15	-.66**	-.38**	.17	.37**
SVF									-.68**	-.55**	-.54**	.07	.30**	-.54**	-.12	-.05
Orientation										.60**	.39**	.25*	-.20*	.57**	-.06	-.01
% Tree Canopy Source Area											-.25*	.34**	.41**	.86**	.19	-.23*
Build Ht. of Source Area												-.34**	-.83**	-.36**	-.02	.49**
Distance to Lake													.28**	.30**	.44**	-.19
Distance to Downtown														.47**	.42**	-.67**
Distance to Industrial															.04	-.49**
Distance to Freeway																-.32**

*. Correlation is significant at the 0.05 level (2-tailed)

**. Correlation is significant at the 0.01 level (2-tailed).

[+] ISA - Impervious surface area
[++] UC - Urban Canyon

To understand the relative cumulative importance of independent factors in determining the difference in air temperature between the neighborhoods and Midway (ΔT_{air}), Ordinary Least Squares (O.L.S.) regression was used to regress five predictor variables in three UHI models against the dependent variable ΔT_{air} for both 2 a.m. and 4 p.m. The independent variables that had the most significant bivariate relationships with ΔT_{air} were used in the 2 a.m. and 4 p.m. UHI models. At 2 a.m. the bivariate correlation analysis suggested that the independent variables of land cover and building configuration factors may be the most important predictors of ΔT_{air}. Based on the bivariate relationships, I had the following O.L.S regression UHI Models at 2 a.m.: Model 1) neighborhood location, Model 2) land cover variables for percent impervious surfaces and percent tree canopy, and Model 3) neighborhood configuration variables for the urban canyon ratio and a dummy variable representing either north-south or east-west orientation (O).

$$\Delta T_{air} = b_0 + b_1N_1 + b2N_2 + b3N_3 + b4N_4 + b5N_5 + b6N_6 + b_7N_7 + b_8I_1 + b_9C_1 + b_{10}U_1 + b_{11}O_1 + e$$

<u>Dependent variable:</u>
ΔT_{air} = Air temperature difference (Neighborhood air temperature - Midway air temperature)
<u>Independent variables</u>:
N = Seven categorical dummy variable to represent the eight neighborhoods
I = Percent impervious surface
C = Percent tree canopy
U = Urban canyon ratio
O = Orientation

At 4 p.m. the bivariate analysis indicated the continued importance of land cover variables, but also the potential impact of adjacent heat sources and sinks. In the afternoon model, I substituted adjacent heat sources and sink variables for building configuration variables. Based on the bivariate relationships, I had the following O.L.S regression UHI Models at 4 p.m.: Model 1) neighborhood location, Model 2) land cover variables for percent impervious surface and percent tree canopy, and Model 3) distance to upwind industrial location and percent tree canopy in the adjacent upwind area.

$$\Delta T_{air} = b_0 + b_1N_1 + b2N_2 + b3N_3 + b4N_4 + b5N_5 + b6N_6 + b_7N_7 + b_8I_1 + b_9C_1 + b_{10}D_1 + b_{11} C_{up\,1} + e$$

<u>Dependent variable:</u>
ΔT_{air} = Air Temperature Difference (Neighborhood air temperature - Midway air temperature)
<u>Independent variables</u>:
N = Seven categorical dummy variable to represent the eight neighborhoods

I = Percent impervious surface
C = Percent tree canopy
D = Distance to industry
C_{up} = Percent upwind tree canopy

To begin the regression analysis, I wanted to understand how controlling for weather affected the explanatory power of each O.L.S regression model. I ran the 2 a.m. and 4 p.m. model using the data from 1) all 62 days, 2) 12 heat events days (clear and cloudy) only, 3) 12 clear days only, and 4) two clear heat event days only. Table 3.5 and 3.6 summarize the results of controlling for different weather conditions at 2 a.m. and 4 p.m. Controlling for weather (clear skies), when urban surfaces are more likely to affect air temperatures, improved the explanatory power of Model Three at both 2 a.m. and 4 p.m. (see Appendices A - D for detailed description of regression tables). At 2 a.m. the adjusted R^2 of Model Three increased from 0.50 using the data from all 62 days to 0.68 using only the data from the 12 clear days. At 4 p.m. the adjusted R^2 of Model Three increased from 0.17 using the data from all 62 days to 0.26 using only the data from the 12 clear days. This analysis confirmed that controlling for weather is a useful practice that improves the explanatory power of UHI regression models. The remainder of the results reported here are from the data with clear skies only (12 clear days and two clear heat event days).

Table 3.5: O.L.S Regression Analysis Comparison for UHI Intensity at 2 a.m. in Eight Chicago Neighborhoods Using Four Different Methods to Calculate UHI Intensities in the Summer 2010

	Midway Clear and Cloudy Days						Midway Clear Days Only					
	All Days (n=62)			12 Heat Event Days* (n=96)			12 Clear Days* UHI (n=96)			2 Clear Days* Heat Events** UHI (n=16)		
	Model 3			*Model 3*			*Model 3*			*Model 3*		
Variable							B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.01	0.02	-0.01	0.01	0.03	0.04	-0.02	0.04	-0.04	-0.04	0.06	-0.08
% Impervious	6.74***	1.18	0.68	5.94***	1.91	0.78	9.66***	2.58	0.82	9.27*	3.34	0.86
% Tree Canopy	-1.38***	0.48	-0.18	-1.90*	0.77	-0.31	-1.79	1.04	-0.19	-3.29*	1.35	-0.38
Urban Canyon	-1.04	0.80	-0.15	-1.75	1.29	-0.33	-1.58	1.74	-0.19	-2.3	2.26	-0.31
Orientation	0.26	0.16	0.11	0.53*	0.26	0.28	0.18	0.35	0.06	0.35	0.45	0.13
(Constant)	-3.89***	0.84		-3.22*	1.36		-5.67***	1.84		-4.46	2.39	
N		496			96			96			16	
Adjusted R2			0.50			0.58			0.68			0.90
Change in R2			0.00			0.02			0.00			0.00

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Table 3.6: O.L.S Regression Analysis Comparison for UHI Intensity at 4 p.m. in Eight Chicago Neighborhoods Using Four Different Methods to Calculate UHI Intensities in the Summer 2010

	Midway Clear and Cloudy Days						Midway Clear Days Only					
	All Days (n=62)			12 Heat Event Days* (n=96)			12 Clear Days* UHI (n=96)			2 Clear Days* Heat Events** UHI (n=16)		
	Model 3			*Model 3*			*Model 3*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	0.02	0.02	0.03	-0.004	0.06	-0.01	-0.04	0.05	-0.07	-0.09	0.16	-0.15
% Impervious	-2.41**	0.90	-0.22	-1.54	2.46	-0.12	-2.2	1.97	-0.2	-2.66	6.31	-0.21
% Tree Canopy	-2.86	1.71	-0.33	-3.09	4.70	-0.29	-0.86	3.75	-0.1	-3.29	12	-0.32
Distance to Industry	-0.68***	0.13	-0.48	-0.69	0.36	-0.41	-.45*	0.18	-0.51	-0.68	0.58	-0.66
Upwind % Tree Canopy	0.02	0.02	0.21	0.02	0.06	0.12	-0.01	0.05	-0.08	0.03	0.15	0.21
(Constant)	4.16***	0.83		3.82	2.29		4.92**	1.83		5.76	5.87	
N		496			96			96			16	
Adjusted R2			0.17***			0.18			.26***			0.12
Change in R2			0.06			0.05			0.09			0.12

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Examining the regression analysis using the 12 clear days only, at 2 a.m. with 96 cases, Model Three explains 68% of the variance in the ΔT_{air} between the neighborhoods and Midway Airport (table 3.7). Overall this model is significant with an F-value of 40.62. The only significant factor in Model Three at 2 a.m. was percent impervious of the block ($p < 0.001$ level). All other variables were not significant predictors of the ΔT_{air} between the neighborhoods and Midway Airport at 2 a.m. Controlling for all other factors, for every 10% increase in impervious surfaces of the block we would expect a warming of the neighborhood relative to Midway by +0.97^{0}C at 2 a.m. This finding confirms other studies showing the contribution of impervious surfaces to warm local temperatures. In addition, in comparison to other land cover factors neighborhood building configuration variables were not significant at 2 a.m. Interestingly, without considering building configuration Model Two had two significant factors, percent impervious ($p < 0.001$ level) and percent tree canopy ($p < 0.05$ level). Without controlling for neighborhood building configuration, tree canopy is a significant predictor of ΔT_{air} .

$\Delta T_{air} = -5.67 - 0.02N_1 + 9.66I_1 - 1.79C_1 - 1.58U_1 + 0.18O_1 + e$ (Model Three)

Table 3.7: Regression Analysis for UHI Temperatures at 2 a.m. in Eight Chicago Neighborhoods during 12 Clear Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-.12*	.05	-.23	-.05	.03	-.09	-.02	.04	-.04
% Impervious				7.42***	1.12	.63	9.66***	2.58	.82
% Tree Canopy				-2.07*	.88	-.22	-1.79	1.04	-.19
Urban Canyon							-1.58	1.74	-.19
Orientation							.18	.35	.06
(Constant)	1.58***	.31		-4.23***	1.11		-5.67***	1.84	
n		96			96			96	
Adjusted R2			.04			.68***			.68
Change in R2						.64			.00

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

At 4 p.m. during the 12 clear days with 96 cases, Model Three explains 26% of the variance in the ΔT_{air} and has one significant predictor (table 3.8). Model Three explanatory power is significantly improves over Model Two for 4 p.m. Overall, Model Three is significant with an F-value of 7.50. In this model, for every additional 1.0 km increase in distance from industrial areas we would expect a neighborhood to be -0.45^{0}C cooler ($p < 0.05$ level). The analysis suggests that predicting daytime ΔT_{air} is more difficult than predicting nighttime ΔT_{air}. In addition, higher wind speeds during the day likely displace temperatures from upwind locations, such as industrial sites.

$$\Delta T_{air} = 4.92 - 0.04N_1 - 2.20I_1 - 0.86\,C_1 - 0.45D_1 - 0.01C_{up1} + e \qquad \text{(Model Three)}$$

Table 3.8: Regression Analysis for UHI Temperatures at 4 p.m. in Eight Chicago Neighborhoods during 12 Clear Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-.05	.05	-.10	-.04	.05	-.08	-.04	0.05	-.07
% Impervious				-1.38	1.68	-.13	-2.20	1.97	-.20
% Tree Canopy				-4.65***	1.32	-.53	-.86	3.75	-.10
Distance to Industry							-.45*	.18	-.51
Upwind % Tree Canopy							-.01	.05	-.08
(Constant)	1.86***	.29		4.00*	1.66		4.92**	1.83	
n		96			96			96	
Adjusted R2			-.00			.17***			.26***
Change in R2						.19			.09

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

I re-ran these models using Sheridan's (2012) Spatial Synoptic Classification (SSC) system for heat events. I had two clear days that were classified as potentially dangerous according to the SSC system. Rerunning the regression model at 2 a.m. with 16 cases, Model Three improved in explanatory power. It explained 90% of the variance in elevated air temperature (table 3.9). Overall the Model Three is significant with an F-value of 27.18. The significant factors during heat wave days were the percentage of impervious surface ($p < 0.005$ level) and percent tree canopy ($p < .01$ level). During heat event days and controlling for all other variables, for every 10% increase in impervious surfaces of the block we would expect a warming of $+0.93^{o}C$. Controlling for all other variables during heat event days, for every 10% increase in tree canopy of the block we would expect a cooling of the neighborhood relative to Midway by $-0.33^{o}C$.

$$\Delta T_{air} = -4.46 - 0.04N_1 + 9.27I_1 - 3.29C_1 - 2.30U_1 + 0.35O_1 + e \quad \text{(Model Three)}$$

Table 3.9: Regression Analysis for UHI Temperatures at 2 a.m. during Heat Events in Eight Chicago Neighborhoods during Two Clear Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-.15	.12	-.31	-.08	.04	-.16	-.04	.06	-.08
% Impervious				6.21***	1.40	.58	9.27*	3.34	.86
% Tree Canopy				-3.47**	1.10	-.40	-3.29*	1.35	-.38
Urban Canyon							-2.30	2.26	-.31
Orientation							.35	.45	.13
(Constant)	1.95*	.71		-2.55	1.39		-4.46	2.39	
n		16			16			16	
Adjusted R2			.03			.91***			.90
Change in R2						.83			.00

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Running the regression model for two clear heat event days at the 4 p.m. with 16 cases, model three explained only 12% of the variance in elevated air temperature (Table 3.10). Overall the model is not significant with an F-value of 1.39. At 2 a.m., during clear heat event days the analysis suggests that the relative importance of land cover variables is higher than during the 12 clear UHI days. Both impervious surface and tree canopy become significant predictors of air temperature at 2 a.m. Yet, all predictors of air temperature are insignificant during heat events in the late afternoon (4 p.m.). This illustrates the lower ability to explain the variance in afternoon air temperatures during heat events. Caution should be exercised when interpreting these results due to the limited number of heat event days in the data set

$$\Delta T_{air} = 5.76 - 0.09N_1 - 2.66I_1 - 3.29\,C_1 - 0.68D_1 + 0.03C_{up1} + e \qquad \text{(Model Three)}$$

Table 3.10: Regression Analysis for UHI Temperatures at 4 p.m. during Heat Events in Eight Chicago Neighborhoods during Two Clear Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-.13	.15	-.21	-.11	0.15	-.18	-.09	.16	-.15
% Impervious				-.68	5.11	-.05	-2.66	6.31	-.21
% Tree Canopy				-5.52	4.02	-.54	-3.29	12.02	-.32
Distance to Industry							-.68	.58	-.66
Upwind % Tree Canopy							.03	.15	.21
(Constant)	2.11*	.87		3.85	5.06		5.76	5.87	
N		16			16			16	
Adjusted R2			-.02			.11			.12
Change in R2						.24			.12

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Conclusion

Land covers, neighborhood building configurations, and adjacent heat sources and sinks are physical characteristics of neighborhoods that affect local air temperatures. This study examined the relative contribution of these physical characteristics to understand what factors researchers and planners should prioritize in neighborhood UHI analysis and UHI reduction programs. The main findings suggest the importance of 1) controlling for weather to isolate urban-induced warming, 2) the relative contribution of individual independent variables to UHI intensities, 3) the diurnal variation in UHI drivers, 4) variations in UHI drivers during heat events, and 5) the lack of association between UHI intensity and income in temperate moist climates. These findings are important for both UHI analysis and reduction efforts.

First, as past research has shown (Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999; McPherson et al., 1997) controlling for weather (clear skies) appears to have isolated the effect of urban warming. This urban warming showed up in the larger ranges I found of ΔT_{air} between neighborhoods and in the O.L.S. regression analysis. Controlling for weather (clear skies) increased the range of UHI intensities (ΔT_{air}) from 2.97°C (5.35° F) (62 days) to 4.15°C (7.88°F) (12 clear days). Controlling for clear skies also increased the explanatory power of the 2 a.m. UHI Model Three (adjusted R^2 = 0.50 for 62 days and adjusted R^2 = 0.68 for 12 clear days). During the day (4 p.m.) the change in the range of UHI intensities (ΔT_{air}) was not as large as at night (from 2.28°C (4.11°F) for all 62 days to 2.85°C (5.13°F) for the 12 clear days). In addition, although the explanatory power of the 4 p.m. UHI Model Three improved controlling for clear skies (adjusted R^2 = 0.17 for 62 days and adjusted R^2 = 0.26 for 12 clear days). ΔT_{air} was still more difficult to predict during the day than at night. For UHI analysis, researchers and planners should control for weather to isolate urban warming from other causes of warming (weather systems, maritime influences, topography, and distance between sites).

Second, bivariate analysis identified the most significant relationships between the individual independent variables of land cover, neighborhood building configuration, and adjacent heat sources and sinks and ΔT_{air} at 2 a.m. and 4 p.m. on the 12 clear days. The two independent variables with the highest correlation with ΔT_{air} at 2 a.m. in the eight Chicago neighborhoods were the percent impervious surface (.82) and percent tree canopy (-.72). The finding on impervious surface bivariate relationship with ΔT_{air} is similar to the correlation Imoff and colleagues (2010) found between impervious surface and the difference in surface temperatures in the Chicago region (explained 89% of the variance in the difference in land surface temperature between urban and rural sites). The percent tree canopy bivariate relationship I found is nearly identical to what Hamada & Ohta (2010) found in Japan, where percent tree canopy in Nagoya explained 72% of the variance in ΔT_{air} at 1 a.m. At 4 p.m. relationships were weaker than at 2 a.m. At 4 p.m. the independent variables with the highest correlation with ΔT_{air} in the eight Chicago neighborhoods were distance to upwind industrial sites (-.52) and adjacent upwind percent tree canopy (-.48). For UHI analysis, these finding provide further evidence of the warming effects of land cover variables on local air temperatures at night and how higher daytime wind speeds complicate late afternoon predictions (Imhoff et al., 2010; Kuttler et al., 1996; Yuan & Bauer, 2007; Dimoudi & Nikolopoulou, 2003; Zhang et al., 2011).

Next, based on the bivariate analysis I choose two land cover variables (percent impervious surfaces and percent tree canopy) and two neighborhood building configuration (urban canyon ratio and orientation) to understand the relative importance of the combination of variables at night. For the afternoon, I choose two land cover variables (percent impervious surfaces and percent tree canopy) and two adjacent heat sources/sinks (upwind distance to industrial and percent tree canopy in the adjacent upwind area) to understand the relative importance of the combination of variables during the day. Through O.L.S. regression analysis I found that land cover variables were more important than neighborhood building configuration variables in predicting ΔT_{air} on clear nights. On the 12 clear days, at 2 a.m. the percent impervious surface was the only significant predictor of $\Delta T_{air.}$ At night, the contribution from impervious surfaces accounted for a +0.97^{o}C increase in air temperature for every 10% increase in amount of impervious surface. Yet, by 4 p.m. percent impervious surface was not a significant predictor of the ΔT_{air} and distance to industry became significant. This finding is a bit higher than what Zhang and colleagues (2011) found at 17 sites in the Detroit area. They found that for every 10% increase in impervious surface area a site warmed by +0.40^{o}C at 5 a.m. and percent impervious was insignificant in the late afternoon (Zhang et al., 2011).

For UHI analysis, this suggests using percent impervious surfaces of a neighborhood to predict UHIs relative to building configuration. I found that building configuration was not a significant predictor of ΔT_{air} in the eight neighborhoods. Building configuration is difficult to change and strategies to decrease impervious pavements and increase vegetation may prove more important in lessening UHI. This is consistent with other research that has shown the benefits of compact development in reducing the growth of

UHIs. Compact development reduces the amount of natural land cover converted to impervious surface and reduces waste heat from the lower energy use that results from compact settlements (Stone et al., 2007; Stone & Norman, 2006). Likewise to reduce UHIs, planners should look to reduce the amount of impervious surface to reduce nighttime air temperatures.

During the afternoon I found different drivers than at night. At 4 p.m., the contribution from upwind industrial sites accounted for a -.45^{0}C decrease in air temperature for every 1.0 km increase in distance from upwind industrial areas. Put another way, warming associated with industrial areas appears to be transported by higher afternoon winds to downwind neighborhoods. Neighborhoods further from industrial areas were cooler than neighborhoods with closer proximity to these areas. Yet, it is unclear from the analysis if the largest influence was from waste heat or large areas of impervious surface relative combined with a lack of vegetation that are common in industrial zones.

For UHI analysis, it is much more difficult to predict afternoon UHI intensities than at night. In addition, researchers should include analysis of upwind factors. For UHI reduction, to reduce afternoon air temperatures, planners should target industrial sites for UHI reduction strategies and address waste heat, high amounts of impervious surface, and lack of vegetation. These findings suggest planners should provide incentives for retrofitting existing industrial sites and require new industrial sites install light or green roofs, permeable pavements, and shade trees to help reduce afternoon air temperatures downwind from industrial areas.

In terms of the variation in the physical drivers of UHI intensity between night and day, many of the differences are likely due to both differences in solar exposure and in wind speeds. At night, light winds and lack of incoming solar radiation likely strengthen localized effects of impervious surfaces. Yet, during the afternoon stronger winds and solar exposure make localized effects less important. During the day higher winds and high solar exposure complicate heating and cooling mechanisms. Higher winds during the afternoon mix the air near the surface. This reduces the influence of local physical characteristics and increases the area of influence. Increasing the effect upwind factors play in contributing to local warming. Researchers analyzing UHIs should avoid using daily averages to examine the physical drivers of UHI intensities, but analyze specific important times of day. Using averages may obscure influential patterns.

Fourth, during two clear heat event days land cover variables continued to be the only significant predictors. The 2 a.m. heat event analysis showed that Model Three explained more of the variance in air temperature difference (90%) than Model Three during the 12 UHI days (68%), while the 4 p.m. heat event analysis showed that Model Three explained less of the variance in air temperature difference (12%) than Model Three from the 12 UHI days (26%). At 2 a.m. both percent impervious surface and tree canopy were significant predictors of air temperature difference during heat events. On clear nights during heat events the percent impervious surface variable indicated a warming effect of +0.93^{0}C for every 10% increase in impervious surfaces. This increase in warmth is similar to the effect of impervious surface on the 12 clear days (+0.97^{0}C for every 10% increase). Yet, unlike the previous analysis for all 12 clear days during the two clear heat events tree canopy becomes a significant predictor of air temperature difference in the eight neighborhoods. Increasing the percentage of tree canopy by 10% in the eight Chicago neighborhoods resulted in a decrease in air temperature difference of -0.33^{0}C during heat events. Yet, no predictors were significant at 4 p.m. UHI analysis should collect weather data on heat event days due to public health implications. In addition, my findings suggest UHI reduction programs in mid-latitude temperate climates, such as Chicago, should prioritize both reductions in impervious surfaces while adding vegetation to reduce nighttime temperatures during heat waves. More longitudinal research is needed on clear heat event days.

Finally, I found that lower income neighborhoods were not more likely to experience elevated air temperatures. This finding contradicts previous research showing a link between UHIs and neighborhood household income levels (Santamouris et al., 2007; Harlan et al., 2006, Solecki et al., 2005; Jenerette et al., 2007). In Chicago's moist temperate climate vegetation does not align with income. The lowest income neighborhood, Bronzeville, with a median household income in 2010 of $19,316 had more tree canopy (18.5%) and was cooler on average at both 2 a.m. and 4 p.m. than higher income neighborhoods Wicker Park ($84,205 with 4.7% tree canopy) and Logan Square ($43,116 with 13.2% tree canopy). Lower income neighborhoods were not associated with lower vegetation and higher air temperatures as in other cities that lie in drier climates where paying for irrigation was key to creating cooler microclimates. Other physical characteristics such as percent impervious surface and the distance to upwind industrial areas were more important in driving elevated air temperatures in the eight Chicago neighborhoods.

For UHI reduction, the biggest finding suggests that removing impervious surface is useful to lower nighttime air temperatures in temperate urban climates, especially on clear summer nights. For instance if the City could reduce the amount of impervious surface in Wicker Park by 5%, 10%, or 15% from its current 95.7%, the 2 a.m. UHI Model Three suggests that Wicker Park is likely to reduce its UHI intensity. Based on predictions form the 2 a.m. Model Three for 12 clear days, Wicker Park air temperature could be reduced from its current + 2.34^{0}C (+4.21^{0}F) from Midway Airport for 95.7% impervious surfaces to 1.77 ^{0}C (+3.16^{0}F) for 90% impervious, 1.28^{0}C (+2.29^{0}F) for 85% impervious, and as low as 0.80^{0}C (+1.42^{0}F) for 80% impervious. Methods to reduce impervious surface may include adding greenroofs, installing permeable pavements on sidewalks, streets, and alleys, and removing any unnecessary impervious pavements. This illustrates the potential positive benefits from addressing the amount of impervious surfaces. The value of this study is that it provides a guide for researchers and planners to understand the relative contribution of using different physical characteristics to predict neighborhood UHIs. In addition, it provides guidance on potentially effective UHI reduction strategies.

Limitations:

This study has three important limitations. First, the number of neighborhoods included in the study was limited to eight. Although I was careful to include different neighborhood physical characteristic types in the study, it does not allow us to make predictions for neighborhoods that substantially differ from the sites. In addition, the small number of sites and the fine scale of the study limit our ability to explain air temperatures between sites. Second, the lake breeze may complicate the analysis. Although I planned the study for July and August when the lake breeze is diminished, from the data the Lake is still a substantial influence even late into the summer. I attempted to account for the Lake's influence by including a variable for distance to Lake. This variable was only significant at night and not during the afternoon when we might expect Lake cooling (Table 3.2). Finally, in the two month period I only were able to capture two heat event days. This limits the confidence in the relationships between heat events and land covers' contribution to air temperature.

Chapter 4

Characterization of Land Covers in Urban Environments: How accuracy affects Urban Heat Island Models

Abstract:

Urban heat islands (UHI) are urban areas that are relatively warmer than rural or suburban areas and create a host of societal impacts during warm weather (Solecki et al., 2005; Stone, 2005; Gartland, 2008; Baik et al, 2000). The UHI effect is due to the conversion of land from rural to urban land covers (Stone, 2012). This makes accurate quantification of land cover types critical to the prediction of UHIs (Akbari et al., 2003). This study examines how different approaches to quantifying land cover types in eight Chicago neighborhoods affects a UHI model's explanatory power. In the summer of 2010, I quantified land cover types using both a two and three-dimensional approach to land cover quantification. A two-dimensional approach treats tree canopy as a land cover, leaving land covers underneath the tree canopy undocumented. A three-dimensional approach takes a layered perspective of urban environments and documents the land cover areas under the tree canopy. Finally, I combined this with in-situ air temperature data to determine the effect accurate calculations of land cover had on explaining elevated air temperatures in the eight Chicago neighborhoods. As expected, I found that on average the three-dimensional approach described land covers better than two-dimensional approaches. On average 14.1% of impervious surface areas went undocumented using a two-dimensional approach. This was especially important in medium density neighborhoods with moderate tree canopies that concealed impervious surfaces below. The most common concealed impervious surfaces were sidewalks, driveways, and parking lots (+6.2%) followed by roads (+6.1%). Yet, I found that a three-dimensional approach did not improve the explanatory power of the UHI model substantially. At 2 a.m. the adjusted R^2 increased from 0.64 for a two-dimensional analysis to 0.68 for a three-dimensional analysis. At 4 p.m. the adjusted R^2 was unchanged. Although a three-dimensional approach provides a more accurate accounting of ground level land covers for urban forestry and rights-of-way planning, this approach can be time consuming and expensive. I found that a less time consuming two-dimensional quantification of land covers is sufficient to predict neighborhood UHIs. This research provides researchers and planners a guide for the level of accuracy required to predict UHIs.

Keywords: Urban Heat Islands, Urban Heat Island Evaluation, Urban Climatology, Heat Vulnerability, Urban Climate Planning

Introduction

Past studies have linked changes to land cover to Urban Heat Islands (UHI) (Stone, 2012; Gartland, 2008; Imhoff et al., 2010; Coseo & Larsen, 2012a) particularly the presence of impervious surfaces and the absence of trees and vegetation. UHIs refer to elevated air temperatures that result from urban materials that increase absorption of solar radiation and change the energy balance of land covers (Stone, 2012; Stewart, 2011). Areas with UHIs are warmer on average relative to surrounding suburban and exurban locations

(Solecki et al., 2005). High air temperatures associated with UHIs negatively impact 1) human health, 2) air and water quality, 3) urban soil quality and tree health, and 4) infrastructure. In addition, high air temperatures indirectly increase the production of waste heat due to air-conditioning and increase energy consumption and water use (Gartland, 2008; Memon et al. 2007; O'Neill et al, 2005, Harlan et al., 2006; Stone, 2012; EPA_b, 2012). Increasingly city officials are concerned with identifying where UHIs exist and understanding how best to lessen the negative impacts.

Many research studies have relied on remotely sensed images to calculate impervious land cover types. Yet, these images are two-dimensional representations of three-dimensional urban spaces. Three-dimensional approaches document land covers beneath tree canopies and roof overhangs, while two-dimensional approaches treat tree canopy as a land cover. Akbari and colleagues (2003) found a more accurate three-dimensional approach documented an additional 17.6% (from 64% to 81.6%) impervious surface land cover types hidden beneath tree canopy in downtown Sacramento, CA. In many cities large amounts of impervious surfaces may be missed by not documenting land covers under tree canopies (Akbari et al., 2003). Yet, past research does not address if accuracy of urban land covers using a three-dimensional approach improves our understanding of UHIs.

For this study I compare two-dimensional characterizations of land cover to three-dimensional approaches to understand the value of using more accurate measures to predict UHIs. I use fine scale aerial images taken in April 2010 to quantify and compare two and three dimensional calculations of land covers on eight Chicago neighborhood blocks. In addition, I collected air temperatures during July and August 2010 to understand the impact of land covers on air temperatures using two and three dimensional approaches. I begin with a literature review of why cities are warmer and then I discuss how previous studies have measured land cover. Finally, I describe the physical characteristics of the eight Chicago neighborhoods. This study investigates two main questions. First, what is the difference in a two-dimensional and three-dimensional approach to calculating impervious surfaces in eight Chicago Neighborhoods? Second, how does documenting impervious surfaces under tree canopies improve a UHI model's explanatory power?

Literature Review

UHI research and analysis requires precise measurements of land cover types to understand the relationship between urban materials and UHIs. In this section I discuss 1) why cities are warmer than rural locations, 2) how land cover is measured, 3) approaches to characterizing land covers in urban environments, and 4) Chicago's urban environment.

Why cities are warmer than rural locations

In the following paragraphs, I will highlight how 1) impervious surfaces differ from 2) vegetated areas and impervious surfaces shaded by tree canopy. Cities are typically warmer than adjacent rural locations as a consequence of converting natural land cover types to urban types. Urban land cover types such as impervious pavements and buildings are made from artificial materials such as concrete, asphalt, masonry, and metals. These urban materials increase local air temperatures by altering the 1) reflectivity (albedo), 2) energy balance (emissivity), and 3) permeability of natural land covers.

First, urban impervious surfaces exposed to full solar radiation tend to absorb and store more incoming shortwave radiation than vegetated areas and shaded impervious surface areas.   Dark pavements such as new asphalt reflect only 5% of incoming light, while absorbing the remaining 95% of incoming solar radiation (EPAa, 2012). Synnefa and colleagues (2007) found that a standard black tiled roof's surface temperature in summer in Athens, Greece was as much as a 10.2 ^{0}C warmer compared to highly reflective tiled roof. In addition, urban land covers alter the energy balance of the land. Once incoming solar radiation is absorbed by urban materials it is converted to stored heat energy. Emissivity is a measure of the ability of materials to emit the stored heat energy. Measured from 0 - 1.0, a value close to 1.0 indicates that a material is effective at storing heat energy and slowly releasing it. Asphalt and concrete pavements have high emissivity values over 0.90, effectively storing and re-emitting energy (asphalt, 0.95-0.971; concrete, 0.90-0.98) (Golden & Kaloush, 2006). Finally, the permeability of land cover is an important factor in the availability of cooling moisture from both vegetation and soils. Impervious land cover materials reduce the available area for planting vegetation and seal soils. Sealing soils limits the exchange of moisture from the soil to the lower atmosphere. Local moisture is important because once heat energy is emitted from urban materials it is released as 1) sensible heat energy, 2) longwave radiation, and 3) latent heat energy (Stone, 2012; Gartland, 2008). Both sensible heat and longwave radiation contribute to UHIs (Stone, 2012). Yet, latent heat energy does not contribute to UHIs. Latent heat energy is formed by evaporation, which is a cooling process (Stone, 2012). Since latent heat is formed by evaporation, its formation is dependent on the presence of local moisture.

The conversion of land from natural to urban land covers results in: 1) more incoming solar energy being absorbed by urban land covers, 2) urban land covers are only able to emit the heat energy in one direction decreasing the rate at which urban covers lose heat energy, and 3) impervious surfaces create dry urban environments resulting in the release of more sensible heat and longwave radiation than more vegetated environments. These three factors contribute to warmer air temperatures in areas with urban cover than in areas with more vegetative cover.

Second, vegetated land covers in urban environments are an important source of both moisture (through evapotranspiration) and shade. Natural land covers role in moderating local climate varies by regional differences in natural land cover types (Imhoff et al., 2010). Semi-arid and desert regions have different climate mechanisms than wetter forested regions. Imhoff and colleagues (2010) examined eight U.S. bioregions and found that the most intense UHIs (8°C) were in regions where forest canopies helped moderate air temperatures through evapotranspiration. The removal of forest and the construction of urban impervious surfaces increased the intensity of UHIs in these regions. Evapotranspiration from soils and plants contribute to the presence of moisture in urban environments, therefore lack of these resources create drier conditions, reduce the formation of latent heat, and enable more of the stored heat energy to be released as sensible heat and longwave radiation (Stone, 2012; Gartland, 2008).

Finally, tree shade also plays a critical role in moderating local air temperatures. Trees reflect, absorb, and diffuse incoming solar radiation shielding urban surfaces from full exposure to solar radiation. Although some natural land covers such as tree canopies may have reflectance values as low as asphalt (reflect 5% of incoming light), tree leaves do not absorb all the non-reflected light due to the structure of the tree. Tree leaves may reflect 5% of the incoming light for dark-leaved plants to as much as 30% for more reflective plant leaves (Geiger et al., 2009). Most Midwestern trees reflect between 22% and 31% of incoming light (table 4.1) (Geiger et al., 2009). Yet, unlike urban materials, trees do not absorb all the non-reflected light (Geiger et al., 2009). Most tree species only absorb around 50% of the incoming shortwave radiation (Geiger et al., 2009). About a third of the total incoming solar radiation hitting the tree passes through the tree canopy as diffuse light reaching the ground below. Although vegetated ground covers such as turf grass lawns reflect from 16% to 26% of incoming light (Oke, 1987), turf grass does not provide the same diffusion of light as tree canopies. So although some tree canopies have similar reflectance values as urban materials such as asphalt and concrete, trees provide other qualities such as diffusion of light, which reduces the absorption and storage of heat energy in urban materials below tree canopies. Finally, vegetated land covers such as turf grass and deciduous trees have similar emissivity values of 0.90 - 0.95 and 0.95 respectively (Oke, 1987; Geiger et al., 2009). Yet, unlike pavements or buildings, leaves have a large surface area and are able to emit radiation in all directions. In addition, past studies have shown that emissivity values of urban materials may be less important than reflectivity in determining surface and air temperatures (Oke et al., 1991; Synnefa et al., 2007).

Table 4.1: Table of Albedo, Absorption, and Diffusion Ratios of Common Street Trees in the Chicago Region - adapted from Geiger et. al., 2009				
Common name	Genus and Species	% Reflectance	% Absorption	% Diffusion
Ash	F. Pennsylvanica	31	51	24
Cottonwood	P. Deltoides	24	50	26
Silver Maple	A. Saccharinum	23	48	29
Tulip Tree	L. Tulipifera	24	52	34
White Oak	Q. Alba	22	44	34
* Reflectance + Absorption + Diffusion = 100% of incoming solar radiation				

Vegetated land covers play two critical roles in urban environments with temperate climates and pre-settlement native forested land covers: 1) to provide moisture through evapotranspiration and 2) to provide shade. These two factors moderate urban air temperatures. In addition, although ground cover shrubs, perennials, and turf grass provide moisture they do not provide as much shading of impervious surfaces as tree canopy. Tree shade may play an important role in shielding impervious surfaces and preventing the absorption of incoming solar radiation in urban materials.

Land cover measurement

Land cover quantification did not occur until after remote sensing became available in the 1960s (USGS, 2012c). The U.S. Geological Survey set up a land use and land cover (LULC) classification system in the 1970s to standardize and document the classification of land using remotely sensed images (Anderson et al., 1976). The USGS uses four levels of classification depending upon the resolution of the remotely sensed image (figure 4.1). The general categories specific to urban land cover at level II include Urban or Built-up Land, Residential, Commercial and Services, Industrial, Transportation, Communications, and Utilities, Industrial and Commercial Complexes, and Mixed Urban or Built-Up Land, Other Urban or Built-up Land (Anderson et al., 1976; USGS, 2012c). One major limitation of the system is that the LULC system assumes that specific land cover types are associated with a general land use type. Similar residential land use density categories may have very different land cover surfaces within the same metropolitan region, yet this is not accounted for in the USGS system. In addition, USGS

LULC categories do not provide enough detail to isolate various surfaces such as pavements, roofs, and vegetated areas. Accurately identifying these land cover types is necessary for UHI models to understand what urban materials are more influential in contributing to higher air temperatures. Despite these generalizations, the USGS has provided useful land cover information and set in place an established system of using remotely sensed images to quantify land cover types.

Classification Level

Typical data characteristics

I.	LANDSAT (formerly ERTS) type of data
II.	High-altitude data at 40,000 ft (12,400 m) or above (less than l:8O,OOO scale)
III.	Medium-altitude data taken between 10,000 and 40,000 ft (3,100 and 12,400 m) (1:20,000 to 1:80,000 scale)
IV.	Low-altitude data taken below 10,000 ft (3,100 m) (more than 1:20,000 scale)

Figure 4.1 - USGS Classification levels for LULC categories - Reprinted from Anderson et al., 1976

Using remotely sensed images provide researchers with a birds-eye-view to document land cover over large spatial areas. All remotely sensed images are captured as a series of pixels. The pixel resolution determines the smallest unique unit area that is discernible. The pixel resolution of remotely sensed images may vary from as much as one pixel representing a 2,700 meter^2 area (Operational Linescan System or O.L.S) to as little one pixel representing a 0.30 meter^2 area (orthoimagery) depending on whether they are from satellites, high altitude flights, or near earth aerials (table 4.2) (Matsuoka et al., 2007, Akbari et al., 2003; Akbari & Rose, 2001a; Akbari & Rose, 2001b; Rose et al., 2003). Due to the pixels, researchers use either a 1) pixel or 2) object oriented classification technique to identify and classify land cover types from remotely sensed images (Geneletti & Gorte, 2003). A pixel oriented technique relies on the resolution of the image pixels to classify land cover types. A pixel oriented technique does not match land cover types with meaningful objects on the ground such as parcels, buildings, or rights-of-ways (Geneletti & Gorte, 2003). This approach results in a coarse analysis that is not as useful for urban forestry and landscape planning of rights-of-way. Both urban forestry and the design of rights-of-way require more detailed information about ground level previous and impervious areas.

The object oriented technique attempts to overcome this limitation. An object oriented technique classifies land cover types by classifying land segments as opposed to land pixels (Geneletti & Gorte, 2003). Geneletti & Gorte write, (2003: 1274) … "[t]he term segment refers to a cluster of adjacent pixels that represents a meaningful object on the terrain, from the user point of view". Parcels, buildings, pavement, and other meaningful objects are more useful for planning purposes than are pixels alone. Geneletti & Gorte (2003) proposed an object oriented technique using both high and low resolution images to classify land cover types. They found using both high and low resolution images in Trento, Italy that they were able to improve the accuracy and reliability of land cover classification by around 2% over using the low resolution Landsat TM alone (Geneletti & Gorte, 2003). Although it did not improve the accuracy by much, they found that using object oriented technique with the higher resolution orthoimagery (7.5 m) resulted in clearer and better delineation between land covers than using the pixel oriented technique with the Landsat TM (30 m) (Geneletti & Gorte, 2003). For urban planning practice an object oriented technique is more useful since analysis of land cover is usually followed up by recommendations for changes to parcels, rights-of-way, pavements, and buildings on the ground. In particular, state and local departments of transportation are often responsible for rights-of-way planning. An accurate account of sidewalk, street, and pervious areas within the rights-of-way is necessary for design purposes. In addition, urban foresters require accurate information of ground level pervious areas available for planting of shade trees. Only certain species of trees are able to survive planting in tree pits.

Approaches to quantifying land covers in urban environments

Researchers use 1) two-dimensional approaches, 2) three-dimensional approaches, and 3) ground based surveys to characterize land covers in urban environments. Table 4.2 is a list of past research describing the type of remotely sensed data used, its resolution, and general approach.

The two-dimensional approach is the most commonly used analysis type and offers the benefit of using coarse or fine resolution image data to analyze large spatial areas. Two-dimensional approaches may use a pixel or object oriented technique (Geneletti & Gorte, 2003). Yet, typically two-dimensional approaches do not generally differentiate between types or levels of vegetation. Tree canopy is usually not distinguished from ground level vegetation and land cover beneath tree canopy is not documented. Common classification systems used in two-dimensional analysis for UHI research include indices such as the Normalized Difference Vegetation Index (NDVI) and the Soil-Adjusted Vegetation Index (SAVI) (Stone & Norman, 2006; Sun et al., 2009; Jenerette et al., 2007). Solecki and colleagues (2005) used a finer scale two-dimensional approach to calculate land cover variables for six single urban blocks in Newark and Camden, New Jersey. Using a two-dimensional approach they found tree canopy cover in the six neighborhoods varied from 10% to 26%, while paved surfaces varied from 18% to 30% and roofed surfaces varied from 19% to 44% (Solecki et al., 2005).

Yet, it is not known how much impervious roof and paved areas went undocumented, especially in the neighborhood with the tree canopy of 26%. In medium to high density neighborhoods with moderate to high percentages of tree canopy, substantial areas of impervious surface under tree canopies may be missed by using a two-dimensional approach (figure 4.2). More accurate three-dimensional approach is much less commonly used but helps account for land covers under tree canopies.

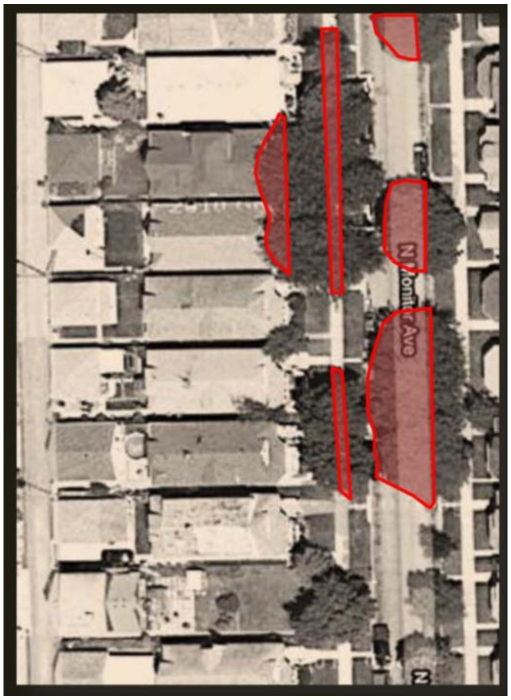

Figure 4.2: Graphic depicting areas of impervious pavement, sidewalk, and roof surfaces concealed by tree canopy. The areas shaded in red go undocumented by two-dimensional approach. Not to scale, for illustration only.
Source: Google Maps, 2012
Illustration: by authors

A three-dimensional approach attempts quantify ground level, multiple roof levels, tree canopy level, and in some cases building walls areas (Rose et al., 2003; Akbari et al., 2003; Nichol & Wong, 2005). To date, most three-dimensional analysis has been at fine scales using aerial images less than 4 meters (Nichol & Wong, 2005). Most of the research comes out of the Lawrence Berkeley National Laboratory's Heat Island Group examination of Sacramento, Chicago, Salt Lake City, and Houston (Akbari et al., 2003; Akbari & Rose, 2001a; Akbari & Rose, 2001b; Rose et al., 2003). The accuracy of land cover classification is improved significantly using a three-dimensional approach (Akbari et al., 2003). Akbari and colleagues (2003) found that documenting the impervious surface areas beneath tree canopy raised impervious surface counts from 64% to 81.6% in downtown Sacramento, CA. Rose and colleagues (2003) found that once impervious surfaces under the tree canopy were quantified that downtown Houston had 58% paved surfaces and 34% roofed surfaces. A similar analysis by Akbari & Rose (2001a) found that the most commonly missed surfaces using a two-dimensional approach in three medium-density Chicago neighborhoods (Wrigleville, Lincoln Park, and Rodgers Park) were grass areas, road, parking lots, and sidewalks. Roof surfaces calculations were not as affected by the type of approach. Roof surfaces were nearly identical in both approaches; trees did not provide a significant amount of concealment of roof surfaces (Akbari & Rose, 2001a). Although this fine scale of analysis makes this approach less desirable for analyzing larger areas, Akbari and colleagues (2003) provided some guidance to sample smaller areas and extrapolate to urban landscapes with similar physical characteristics.

A final approach is based on ground surveys of small areas or a few samples. At a very fine scale some researchers use ground surveys to document land cover classes (Chang et al., 2007; Geneletti & Gorte, 2003). Again the limitation here is that the scale of analysis is quite small. Several researchers have used ground surveying in combination with aerial or satellite data to ground truth a few samples of land cover types (Chang et al., 2007; Geneletti & Gorte, 2003). Yet, what is missing from the research to date is a rigorous assessment of whether using more accurate three-dimensional approaches to calculating land cover improves our understanding of UHIs.

Table 4.2: Approach to Quantifying Land Cover Types by Author

Authors	City or Region	Remotely Sensed Image	Image Pixel Resolution (m)	Two-dimensional	Three-dimensional	Ground Survey	Remote sensing used but approach not specified
Akbari et al., 2003	Sacramento, CA	Orthoimagery	0.3		X		
Akbari & Rose, 2001a	Chicago, IL	Orthoimagery	0.3		X		
Akbari & Rose, 2001b	Salt Lake City, UT	Orthoimagery	0.3		X		
Chang et al., 2007	Taipei City, Taiwan	Ground survey and aerials	NS*			X	X
Chen et al., 2006	Pearl River Delta, China	IKONOS 2000	4	X			
Geneletti & Gorte, 2003	Trento, Italy	Landsat TM & Orthoimagery	(Landsat), 7.5 m (Ortho)	X		X	
Gill et al., 2008	Manchester, England	"Cities Revealed" Aerial	0.25	X			
Imhoff et al., 2010	38 Bioregions	Landsat 7 ETM+ and IKONOS	30(Landsat), 4(IKONOS)	X			
Li & Weng, 2007	Indianapolis, IN	Landsat 7 ETM+	NS*				X
Liang & Weng, 2011	Indianapolis, IN	Landsat 7 TM & ETM+	NS*				X
Matsuoka et al., 2007	Yellow River, China	MODIS and OLS	250 (MODIS), 2,700 (OLS)				X
McPherson et al., 1994	Chicago, IL	Satellite and Aerials	NS*			X	X
Nichol & Wong, 2005	Hong Kong	IKONOS	4		X		
Nowak & Greenfield, 2012	20 U.S. Cities	Aerials	0.15 - 2	X			
Nowak et al., 1996	58 U.S. Cities	Aerials	NS*	X			
Rose et al. , 2003	Houston, TX	Orthoimagery	0.3		X		
Solecki et al., 2005	Newark and	Aerials	NS*	X			
Yuan & Bauer, 2007	Minneapolis, MN	Landsat 5 TM, Landsat 7 ETM+, and Orthoimagery	120 (Landsat 5), 60 (Landsat 7), 1 (Ortho)	X			

* Not Specified
IKONOS - is derived from the Greek word for image
MODIS - Moderate Resolution Imaging Spectroradiometer
OLS - Operational Linescan System

Chicago's urban environment

The Chicago-Joliet-Naperville metropolitan statistical area is an urbanizing area of with a 2010 population of 9,461,105. Up 4% from 2000 (U.S. Census, 2012), most of this growth is taking place at the rural fringe of the metropolitan area. Even though the region's population is growing, the population of the City is down 6.9% from 2000 to 2,695,598 residents in 2010 (Census2010, 2012). The average population density is down as well. In 1980 Chicago had 51.1 persons per hectare (20.67 persons per acre) by 2010 Chicago's population density was down to only 45.7 persons per hectare (18.5 persons per acre) (U.S. Census, 2012).

The Chicago region lies on a flat lake plain (41^{0} 52' 55" North and 087^{0} 37' 40" West (USGSa, 2012)) with average elevation of 190.80 m (625 ft.) above sea level (ranging from 176.5 m (579 ft.) to 205.1 m (673 ft.)) (USGSb, 2012). The average mean temperature from May to September is 25.9^{0}C (1961-1990) (Hayhoe et al., 2010a). Historically a mixture of prairie and temperate forest land covers played an important role in moderating air temperatures and precipitation in the region. European settlement introduced impervious surfaces and planted trees in place of prairie landscapes. Residents and municipal tree and shrub planting habits have increased regional forest cover from presettlement tree coverage of 13% to 20% as of the mid 1990s (McPherson et al., 1997). In the city of Chicago, tree canopy covers 11% of the land area on average, which is slightly lower than presettlement conditions (McPherson et al, 1997). Yet, the tree canopy coverage is not necessarily determined by amount of pervious planting areas and may vary greatly within the city. Akbari & Rose (2001_a) found that tree canopy in medium to high density Chicago neighborhoods varied from as low as 3.7% in Pilsen to as much as 13% in Wrigleyville. More recent studies by Nowak & Greenfield (2012) found that the Chicago region's 2009 tree and shrub coverage (18%) was less than the average of 28.2% for the 20 U.S. cities. Nowak and Greenfield also found that Chicago, like other cities in the study had lost tree canopy within the five year period. Between 2005 to 2009, the tree canopy declined by .5% (table 4.3). This decline is similar to declines in vegetative cover in other north central U.S. cities (Detroit, -0.7%, Minneapolis, -1.1%, Kansas City, -1.2%) (Nowak & Greenfield, 2012).

Table 4.3: Urban Land Cover Change for 20 U.S. Cities* Compared to Chicago from Nowak & Greenfield (2012)				
Land Cover Type	Average % for 20 Cities* in 2009	Average % for Chicago in 2009	Change in % between 2005 and 2009 for 20 Cities	Change in % between 2005 and 2009 for Chicago
Grass/Herbaceous Cover	24.7%	20.7%	0.5	-0.1
Tree/Shrub Cover	28.2%	18.0%	-1.5	-0.5
Impervious Buildings	15.9%	26.8%	0.3	-0.3
Impervious Roads	12.3%	12.1%	0.3	0.0
Impervious Other	14.8%	19.6%	0.8	0.3
Water	0.1%	0.2%	0.1	0.2
Bare Soil	4.0%	2.6%	-0.3	0.4

* 20 cities included in the study
Albuquerque, NM
Atlanta, GA
Baltimore, MD
Boston, MA
Chicago, IL
Denver, CO
Detroit, MI
Houston, TX
Kansas City, MO
Los Angeles, CA
Miami, FL
Minneapolis, MN
Nashville, TN
New Orleans, LA
New York, NY
Pittsburgh, PA
Portland, OR
Spokane, WA
Syracuse, NY
Tacoma, WA

Nowak & Greenfield (2012) found that impervious covers remained largely unchanged in the Chicago region from 2005 to 2009. A more detailed land cover analysis in 2000 of 14 City of Chicago neighborhoods (Gray & Finster, 2000) found that roofs constituted 29.8% to 36.9% of land cover types while pavement made up 18.32% to 25.62% of the land cover types. The Chicago Department of Transportation reports that Chicago's rights-of-way made up 23% or 33,256 acres of the City's land area (Attarian, 2008). Alley public rights-of-way constitute about 2.4% of all land in the City or 3,500 acres (Attarian, 2008). While Akbari & Rose (2001a) used the same orthoimagery as Gray & Finster (2000) they used a three-dimensional approach. They found that impervious surfaces varied between different medium to high density Chicago neighborhoods (table 4.4). Roofs covered from a low of 19.2% of surfaces in Garfield Park to as much as 34.4% in Pilsen (Akbari & Rose, 2001a). They found that roads covered from 12.4% of surfaces in Rodgers Park to as much as 23.3% of surfaces in Wrigleville. All pavements covered between 23.3% of surfaces in Rodgers Park to as much as 32.9% in Wrigleville (Akbari & Rose, 2001a).

Table 4.4 - Three-Dimensional Orthoimagery Land Cover Analysis of Three Medium Density Chicago Neighborhoods in 2000 from Akbari & Rose (2001a)

	Cover-type (percent of total cover)								
	Roof	Road	Parking Area	Sidewalk / Driveway	Private Surfaces	Tree Cover	Grass	Barren Land	Misc
Garfield Park	19.2	15.0	3.7	7.1	3.1	5.9	38.7	8.5	4.8
Lincoln Park	33.8	18.5	4.3	4.6	0.0	8.5	30.6	0.0	8.2
Pilsen	34.4	22.3	4.0	7.7	0.3	3.7	26.9	1.7	2.6
Rodgers Park	28.2	12.4	5.4	4.7	0.8	9.8	45.1	2.8	0.5
Wrigleyville	32.4	23.3	4.2	4.8	0.6	13.0	23.3	0.6	10.6

Research Questions

This study examines how using three-dimensional land cover characterizations impact descriptions of urban environments for UHI predictions. Specifically I investigate two research questions. First, what is the difference between two-dimensional and three-dimensional characterization of impervious surfaces in eight Chicago Neighborhoods? I anticipate that using a more accurate three-dimensional approach to account for the impervious surfaces will significantly increase the accuracy of land covers characterizations in the eight neighborhoods. Next, how does accounting for impervious surfaces under tree canopies with the three-dimensional approach improve the UHI model's explanatory power? I expect that more accurate three-dimensional calculations of impervious surface area will improve the UHI models explanatory power.

4.0 Methods

4.1. Neighborhood selection

We selected neighborhood cases based on: 1) a neighborhood's likelihood of developing UHIs, 2) income levels, and 3) demographic variation. First, I used a City of Chicago 2006 study of surface temperatures to select neighborhoods where UHIs may be more likely to occur. I selected neighborhoods within 1,000 ft. of an elevated surface temperature area based on a City of Chicago 2006 study (Chicago, 2006). Second, the neighborhoods were divided into low (less than $26,405), median (between $26,406 and $52,809), and high (greater than $ 52,810) income neighborhoods based on 2000 U.S. census data and a study by the Institute for Housing Studies, DePaul University (IHS, 2009). Finally, I divided those neighborhoods into majority African American (total population is greater than 67% African American) or non-majority African American (total population is less than 21% African American) neighborhoods based on 2000 U.S. census block group data. The final eight selected neighborhoods were Belmont Cragin, Austin, Logan Square, Wicker Park, Little Italy, Bronzeville, Beverly, and East Side (figure 4.3). I had one exception to the three criteria. I choose Beverly because it had higher percentages of tree canopy and lower percentages of impervious surface area. Finally, I selected one representative block within each neighborhood for which to calculate physical characteristics.

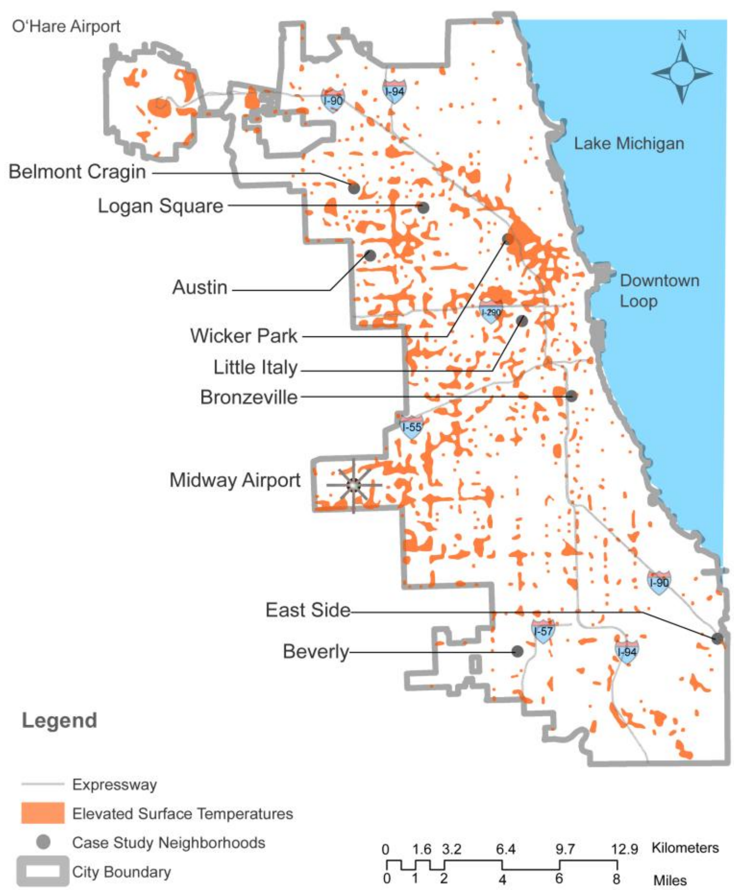

Figure 4.3: Map illustrating the city of Chicago limits, the eight study neighborhood, Midway Airport, and the heterogeneous distribution of elevated surface temperatures from a City of Chicago Department of the Environment 2006 study.
Data source: City of Chicago Department of Environment GIS database, accessed February 1, 2010
Illustration: by authors

Neighborhood physical characteristics

Table 4.5 describes the eight selected blocks' land cover and other physical properties I used in the analysis. Most of the case blocks are comparable in size. However, the Bronzeville block size varied from 5,254 m^2 for the case block to a 40,162 m^2 for the control block. The neighborhood with the most impervious surface (including impervious surface under tree canopies) was Wicker Park. Both the Wicker Park and Little Italy blocks were approximately 95% impervious. Beverly had the least amount of impervious surfaces with less than 55% impervious surface. Wicker Park had the lowest amount of tree canopy (4.8%) while Beverly had the most tree canopy (60%).

Weather observation instruments

We used stationary 1) HOBO weather stations and 2) Chicago's Midway Airport weather data to understand air temperature differences in the eight neighborhoods. First, I acquired 24 hour weather observations using stationary Onset U23-002 HOBO External Temperature/RH Data Logger with sensor weather station and a model RS3 solar radiation shield. Each HOBO was located at the center of each selected block's back alley attached to a utility pole at three meter height. The HOBO collected ambient air temperature and relative humidity from July 1 to August 31, 2010 every 5 minutes for 24 hours a day. HOBOs were placed well below the building heights for each neighborhood. All building heights were a minimum 9.14 meters. The accuracy of the HOBO weather stations was $\pm 0.2^0$C from 0 to 50^0C with relative humidity accuracy of ±2.5% from 10 to 90% relative humidity (Onset, 2010). Second, I collected Midway Airport hourly weather observations from July 1 to August 31 from MetroWest (2012). Midway provides a base case before air moves over the neighborhoods because during warm weather predominate wind direction is out of the southwest direction (210 degrees).

Data collection procedures

Data collection procedures for the weather instruments include locating the device, installing, and recording weather data. First, HOBO units' location and heights were placed using the *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites* criteria (Oke, 2006) to establish the most representative location for neighborhood air temperatures near the ground. Each weather unit was mounted above the height of garbage collection trucks at three meters on the north or east side of a utility pole. Two screws and two zip ties were used to secure the solar radiation shield to the utility pole. The data logger with the logger window facing upwards was zip tied to the pole as well. Every two weeks weather data was down loaded to a laptop computer using a HOBO data shuttle.

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4.5 Quantifying neighborhood physical characteristics

We used USGS high resolution (1.0 m) orthoimagery from April 9, 2010 to calculate all land cover percentages. I based the two and three-dimensional characterization of land cover types on Akbari and colleagues (2003) approach to calculating above-the-canopy (two-dimensional) and under-the-canopy (three-dimensional) land covers. Land covers were calculated twice for each case study block, once for two-dimensional analysis and once for three-dimensional analysis. All calculations were a percentage of the whole block including a portion of the street's impervious surface extending from street curb to mid street. For the two-dimensional analysis, the land cover types included 1) roof, 2) road, 3) alley, 4) sidewalks, driveways, and parking lots, 5) tree canopy, and 6) planting areas. For the three-dimensional analysis I excluded tree canopy and calculated five land cover types in sun and under tree shade: 1) roof, 2) road, 3) alley, 4) sidewalks, driveways, and parking lots, and 5) planting areas. I did not distinguish between sidewalks, driveways, and parking lots because of the small number of private driveways and parking lots. I calculated the density of units per hectare from 2010 census tract data for each neighborhood. Calculations for tree canopy only include deciduous shade and coniferous trees. The UHI intensity or the difference in temperature between each neighborhood and Midway (ΔT_{air}) was calculated for 2 a.m. and 4 p.m. for 12 clear days in July and August, 2010.

Table 4.5: Descriptive Statistics of Three-Dimensional Characterization of Land Cover in 2010 for Eight Chicago Neighborhoods

Neighborhood	Density Units/ hectare	Block Area m^2	Impervious Surface Area m^2	Tree Canopy Area m^2
Wicker Park	47.4	13,462	12,879	637
Bronzeville	35.7	40,162	32,086	7,425
Austin	35.3	19,794	14,873	3,906
Little Italy	30.9	20,604	19,436	6,062
Logan Square	27	25,821	22,739	3,415
Belmont Cragin	26	23,219	18,104	4,212
East Side	19.2	19,468	14,325	4,501
Beverly	14.3	22,678	12,391	13,702
Average	32.0	23,151	18,354	5,482

Table 4.6: Descriptive Statistics of Two (2-D) and Three-Dimensional (3-D) Characterization of Land Cover Variables in 2010 for Eight Chicago Neighborhoods

Cover-type (percent of total cover for two-dimensional and percent increase using three-dimensional)

Neighborhood	% ISA		Roof		Road		Alley		Sidewalks, driveways, and parking lots		Tree Canopy	Planting areas	
	2-D	3-D	2-D	3-D	2-D	3-D	2-D	3-D	2-D	3-D	2-D	2-D	3-D
Little Italy	66.5	+27.8	38.3	+0.8	3.2	+14.1	4.1	+0.1	20.9	+12.8	29.4	4.1	+1.6
Beverly	28.9	+25.7	16.3	+6.6	4.5	+7.1	1.6	+3.1	6.5	+9.1	60.4	10.7	+34.7
East Side	59.8	+13.8	31.0	+0.9	7.5	+7.0	3.7	+0.1	17.6	+5.9	23.1	17.1	+9.3
Belmont Cragin	66.2	+11.8	36.9	+1.0	6.7	+6.6	4.0	+0.1	18.6	+4.1	18.1	15.7	+6.4
Bronzeville	69.5	+10.4	21.6	+0.2	12.6	+4.3	4.2	+0.3	31.2	+5.6	18.5	12.0	+8.1
Austin	65.5	+9.6	27.1	+1.1	10.9	+3.5	4.1	+0.1	23.4	+5.0	19.7	14.8	+10.1
Logan Square	78.8	+9.3	37.3	+0.6	11.9	+4.9	7.0	+0.01	22.6	+3.8	13.2	8.0	+4.0
Wicker Park	91.4	+4.3	34.0	+0.02	23.8	+1.1	6.2	+0.1	27.4	+3.0	4.7	3.9	+0.5
Average	65.8	+14.1	30.3	+1.4	10.1	+6.1	4.4	+0.5	21.0	+6.2	23.4	10.8	+9.3

Results

First, I wanted to understand how accounting for impervious surfaces under tree canopies affected calculations of roof, roads, alley, and sidewalks, driveways, and parking lot impervious surfaces. Table 4.6 describes percent land cover types using a two-dimensional and a three-dimensional approach.

For the eight neighborhoods, the average percent impervious surface calculated using a three-dimensional approach (75.9%) was +14.1% higher than using a two-dimensional approach (65.8%). In neighborhoods with the highest amount of tree canopy (60% tree canopy in Beverly and 30% tree canopy in Little Italy) more than 25% of impervious surfaces were missed. Wicker Park had the smallest amount of undocumented impervious surfaces. Undocumented impervious surfaces in Wicker Park were only 4.3% of the total land cover. Although both Little Italy and Wicker Park have high amounts of impervious surface, Little Italy has substantially greater tree canopy coverage than Wicker Park. I ran a t-test on the paired difference in the means of the percent impervious surface for all the neighborhoods using the two approaches (table 4.7). I found that overall the difference of using a three-dimensional approach was significantly different ($p < 0.000$ level) than using a two-dimensional approach.

Table 4.7: Paired Samples Test of the Difference in Percent Mean Impervious Surface Area for Eight Chicago Neighborhoods using a Two Compared to Three-dimensional Approach

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Dev.	Std. Error Mean	Lower	Upper	T	df	Sig. (2-tailed)
Pair 1	% impervious calculated with three-dimensional approach - % impervious calculated with two-dimensional approach	.141	.078	.008	.125	.157	17.714	95	.000

Overall, using a two-dimensional approach the most commonly missed impervious land cover types were sidewalks, driveways, and parking lots (6.2%) followed closely by roads (6.1%). Yet, this did not necessarily vary only with tree canopy. Beverly had the highest percent tree canopy. Yet, Beverly's low density (11.7 units/hectare) resulted in planting areas (lawns or gardens) being the most undocumented land cover types (increasing by +34.6% with a three-dimensional approach). Little Italy with the second highest density (43.7 units/hectare) also had the second highest percent tree canopy (29.4%). By documenting impervious surfaces under tree canopies the calculations of road surfaces went from 3.2% (two-dimensional) to 17.3% (three-dimensional) of total cover types (increasing by +14.1%) and sidewalks, driveways, and parking lots went from 20.9% to 33.7% of total cover types (increasing by +12.8%). The combination of moderate to high tree canopy and high density resulted in substantial areas of impervious surface to go undocumented in Little Italy by using a two-dimensional approach. Documenting impervious surfaces under tree canopies significantly improved the description of impervious land covers in medium density neighborhoods with moderate to high amounts of tree canopy.

Yet, I found that using a three-dimensional approach is not as critical to accurately describe impervious land cover types in a neighborhood with either 1) low amounts of tree canopy such as Wicker Park or 2) higher percentages of tree canopy and lower density of units per hectare such as Beverly. In addition, roofs and alleys were the least affected by tree canopy concealment. With the exception of Beverly, the lack of tree canopy adjacent to the alleys resulted in little, if any, difference between the calculations. Although using a three-dimensional approach provides a more accurate account of impervious surfaces in neighborhoods with heavy tree canopies and higher densities, I wanted to know how documenting impervious surfaces under tree canopies affects a UHI model's explanatory power.

Next, I examined if characterizing land cover variables using a three-dimensional approach improved the explanatory power of a UHI model over using a two-dimensional approach. I took a UHI model used in a related study of Chicago UHIs (Coseo & Larsen, 2012a) to test the different approaches. I regressed five predictor variables in blocks against the difference in air temperature (ΔT_{air}) between the eight neighborhoods and Midway Airport for 2 a.m. and 4 p.m. for 12 clear days in the summer of 2010.

At 2 a.m. the predictor variables entered included block 1) neighborhood location, block 2) land cover variables for two-dimensional percent impervious surfaces and percent tree canopy, block 3) neighborhood configuration variables for the urban canyon ratio and a dummy variable representing either north-south or east-west orientation. At 2 a.m. substituting the three-dimensional calculations for the two-dimensional calculations of percent impervious surface increased the explanatory power slightly from 0.64 (two-dimensional, table 4.8) to 0.68 (three-dimensional, table 4.9). Running the model with the two-dimensional and the three-dimensional calculations did not affect the significant predictors. Percent impervious surface was the only significant predictor using both two and three dimensional approaches. Both methods had similar coefficients for percent impervious of 9.75 (two-dimensional) and 9.66 (three-dimensional). Controlling for all other factors, for every 10% increase in two-dimensional and three-dimensional calculations of impervious surfaces of the block we would expect a warming of the neighborhood relative to Midway by +0.97^{o}C at 2 a.m. At 2 a.m. using the more accurate three-dimensional land cover calculations for impervious surface area did not result in significantly greater explanatory power, the predictors were the same, and the coefficients were identical.

Table 4.8: Regression Analysis for UHI Temperatures at 2 a.m. using Two-Dimensional Approach in Eight Chicago Neighborhoods in Summer 2010

Two-Dimensional Analysis

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.12***	0.05	-0.23	-0.09**	0.03	-0.17	-0.11***	0.04	-0.20
% two-dimensional Impervious				10.41***	1.90	1.19	9.75*	4.70	1.11
% Tree Canopy				4.13*	2.05	0.44	4.47	4.01	0.47
Urban Canyon							1.01	1.75	0.12
Orientation							-0.40	0.31	-0.14
(Constant)	1.58*	0.31		-6.41***	1.73		-6.17	3.51	
n			96			96			96
Adjusted R2			0.04			0.64***			0.64
Change in R2						0.60			0.01

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Table 4.9: Regression Analysis for UHI Temperatures at 2 a.m. using Three-Dimensional Approach in Eight Chicago Neighborhoods in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.12*	0.05	-0.23	-0.05	0.03	-0.09	-0.02	0.04	-0.04
% three-dimensional Impervious				7.42***	1.12	0.63	9.66***	2.58	0.82
% Tree Canopy				-2.07*	0.88	-0.22	-1.80	1.04	-0.19
Urban Canyon							-1.58	1.74	-0.19
Orientation							0.18	0.35	0.06
(Constant)	1.58***	0.31		-4.23***	1.11		-5.67***	1.84	
n		96			96			96	
Adjusted R2			0.04			0.68***			0.68
Change in R2						0.64			0.00

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Similarly at 4 p.m. I found only slight variation using the more accurate calculations. At 4 p.m. the predictor variables entered included block 1) neighborhood location, block 2) land cover variables for two-dimensional percent impervious surfaces and percent tree canopy, block 3) adjacent heat sources and sinks variables for the distance to industry and upwind percent tree canopy variable representing air displacement form upwind locations. At 4 p.m. substituting the three-dimensional calculations for the two-dimensional calculations of percent impervious surface left the explanatory power unchanged from 0.26 (two-dimensional, table 4.10) to 0.26 (three-dimensional, table 4.11). Similar to 2 a.m., running the model at 4 p.m. with the two-dimensional and the three-dimensional calculations did not affect the significant predictors. Using both two and three dimensional approaches distance to industry remained the only significant predictor. At 4 p.m. the coefficients for distance to industry were slightly different with coefficients of -0.37 (two-dimensional) and -0.45 (three-dimensional). Using the two-dimensional calculations during the afternoon, for every 1.0 km increase in distance from upwind industrial areas a neighborhood's air temperature was -0.37^{0}C cooler compared to -0.45^{0}C cooler using a three-dimensional approach. Just as at 2 a.m., at 4 p.m. using the more accurate three-dimensional land cover calculations for impervious surface area did not result in significantly greater explanatory power, the predictors were the same, and the coefficients were similar in scale. For UHI predictive models, overall I found that using more accurate three-dimensional characterization of impervious surface calculations did not significantly improve the models performance at either 2 a.m. or 4 p.m.

Table 4.10: Regression Analysis for UHI Temperatures at 4 p.m. using Two-Dimensional Approach in Eight Chicago Neighborhoods in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.05	0.05	-0.10	-0.03	0.05	-0.06	-0.03	0.05	-0.05
% two-dimensional Impervious				-5.84*	2.64	-0.71	-4.27	2.92	-0.52
% Tree Canopy				-9.85***	2.84	-1.12	-4.49	5.21	-0.51
Distance to Industry							-0.37*	0.16	-0.42
Upwind % Tree Canopy							-0.01	0.04	-0.09
(Constant)	1.86***	0.29		7.93*	2.40		6.62*	2.56	
n		96			96			96	
Adjusted R2			-0.00			0.21***			0.26*
Change in R2						0.23			0.07

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Table 4.11: Regression Analysis for UHI Temperatures at 4 p.m. using Three-Dimensional Approach in Eight Chicago Neighborhoods in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.05	0.05	-0.10	-0.04	0.05	-0.08	-0.036	0.049	-0.072
% three-dimensional Impervious				-1.38	1.68	-0.13	-2.10	1.97	-0.20
% Tree Canopy				-4.65***	1.32	-0.53	-0.86	3.75	-0.10
Distance to Industry							-.45*	0.18	-0.51
Upwind % Tree Canopy							-0.01	0.05	-0.08
(Constant)	1.86***	0.29		4.00*	1.66		4.92**	1.83	
n		96			96			96	
Adjusted R2			-0.00			.17***			.26***
Change in R2						0.19			0.09

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Conclusion

In the eight neighborhoods, the three-dimensional approach on average resulted in the documentation of an additional +6.2% sidewalks, driveways, and parking lot surfaces and an additional +6.1% road pavement surfaces. Yet, neighborhood tree canopy alone does not necessary explain all of the differences in concealing impervious surfaces. I found that it was a combination of density and tree canopy that resulted in concealing many of the impervious surfaces. For example, I found that using a three-dimensional approach was more useful in Little Italy where a combination of moderate tree canopy (30%) and high densities (43.7 units/hectare) obscured more impervious surfaces than in Wicker Park with low tree canopy (4.7%) and high densities (63.5 units/hectare). In Little Italy, substantial areas of impervious roads (+14.1%) and sidewalks, driveways, and parking lots (+12.8%) went undocumented by using a two-dimensional approach. These are generally more than the additional +11% paved areas that Akbari and colleagues (2003) found in downtown Sacramento, CA. They also examined eight residential neighborhoods. The neighborhood (East Downtown) with the most impervious surface had just less than 70% impervious surface (accounting for land covers under the tree canopy) and 27% tree canopy. Accounting for under the canopy road surfaces raised percentages of roads by +9.5% over two-dimensional analysis (Akbari et al., 2003). This is similar to the findings for Little Italy. Lastly, I found using a two-dimensional approach generally represented an accurate account of percent roof and alley surfaces. The exception was in lower density neighborhoods with lower building heights and high amounts of trees. In Beverly, I found a three-dimensional approach documented an additional +6.6% roof surfaces and +3.1% of alleys surfaces. High density neighborhoods with taller buildings and mature street trees planted in wells, such as Little Italy, primarily obscured ground level impervious surfaces.

Finally, I found that using three-dimensional characterizations of land covers did not substantially improve the explanatory power of a UHI model. Past studies of three-dimensional approaches have not tested more accurate characterization of impervious surface calculations to understand how they might improve UHI models (Akbari et al., 2003; Akbari & Rose, 2001a; Akbari & Rose, 2001b; Rose et al., 2003; Nichol & Wong, 2005). Running the UHI model with both two-dimensional and three-dimensional calculations percent impervious surface improved the explanatory power slightly at 2 a.m., but decreased the explanatory power slightly at 4 p.m. At 2 a.m. the UHI model improved from 0.64 (two-dimensional) to 0.68 (three-dimensional). At 4 p.m. the UHI model remained unchanged from 0.26 (two-dimensional) to 0.26 (three-dimensional). This suggests that using three-dimensional characterization of land cover variables does not substantially improve UHI models over using two-dimensional characterizations. It also suggests that shading provided by urban forests may shield impervious surfaces from absorbing incoming solar radiation, thus preventing these surfaces from contributing substantially to UHIs.

For UHI analysis, although the three-dimensional approach more accurately describes ground level land covers, the findings suggest that two-dimensional calculations of land cover variables are likely sufficient for predicting UHIs. Yet for UHI reduction, the three dimensional approach to quantifying land cover types improves the description of ground level land covers, which is important for tree and vegetation planting programs, programs to reduce impervious surface areas, stormwater management programs, and programs to change land cover type. This is especially the case where a combination of moderate to high tree canopies obscure impervious surfaces in dense urban areas.

Limitations:

This study has at least three limitations. First, I were only able to document in detail eight neighborhoods. Second, tree type was not considered in this analysis. Tree type likely would affect the diffusion of incoming shortwave radiation that reaches under lying impervious surfaces. Finally, this study did not include land surface temperatures derived from satellite imagery. Future research should consider adding more neighborhoods, documenting tree type, and combining this analysis with land surface temperatures.

Chapter 5

Quantifying the Impact of Cool Pavement Strategies on Urban Heat Islands in Chicago Neighborhoods

Abstract:
Compact city form is viewed as a necessary step in advancing global sustainability. However, compact settlements have high percentages of impervious pavement that tend to increase urban heat islands (UHI) (Oke, 1987). UHIs are the occurrence of relatively higher local air temperatures due to urban surfaces. Past research has shown that UHIs increase heat related illness and mortality (Harlan et al., 2008; Stone, 2005; Stone & Rodgers, 2001; Gartland, 2008; Alberti, 2009). This paper quantifies the impact of a cool paving program in Chicago, the Green Alley Program (GAP), designed to reduce UHIs. During the summer of 2010, temperature readings were taken from mobile and fixed weather stations in 16 alleys in eight Chicago neighborhoods to understand how cool pavement interventions impact air temperatures. In each of the eight neighborhoods, temperatures were collected in one alley with light colored and/or pervious paving and in another nearby alley with similar urban density and form but without the cool paving intervention. Through mobile measurements, I found that the alley's pavement temperature explained over 64% of the variance in air temperature. This relationship increased to explain over 84% of the variance in air temperature under light wind conditions. Pavement temperatures affect air temperatures, especially under light wind conditions. In addition, I found that air temperatures were -0.61^0 C (1.1^{0}F) cooler over new high albedo concrete when compared to conventional aged asphalt pavements. Porous concrete provided comparable cooling effect (-0.39^0 C (0.71^{0}F) lower than air temperature over aged asphalt). The value of this work is that it provides a fine scale method for the comparison of different pavement types and how they differentially contribute to elevated air temperatures. These findings contribute to a growing body of knowledge about cool paving designs and increase our understanding of how physical planning and design can enhance the viability, livability, and sustainability of compact city form.

Keywords: Urban Heat Islands, Urban Climatology, Heat Vulnerability, Cool Pavements, Green Infrastructure

Introduction

Many researchers and planners view compact city form as a necessary step in advancing global sustainability (Wheeler, 2001; Ewing, 1997; Beatley, 2000; Berke, 2002). Yet, compact settlements have high percentages of impervious surface in the form of pavements and buildings. Urban areas made from conventional pavements and other impervious materials alter the reflectivity and energy balance of the land creating relatively warmer microclimates called urban heat islands (UHI) (Stone, 2012; Oke, 1987; Jenerette et al., 2007; Stone et al., 2007, Stone & Rodgers, 2001). UHIs are areas of urban climate where surface and air temperatures tend to be warmer than in adjacent areas (Oke, 1987). UHIs are most problematic during warm weather when people living or working in these areas are exposed to elevated air temperatures. Elevated air temperatures are potentially dangerous because they cause increased human health and societal problems (Harlan et al., 2008; Stone, 2005; Stone & Rodgers, 2001; Gartland, 2008; Alberti, 2009). While adding vegetation reduces the UHI (Solecki et al., 2005), many urban areas have limited planting space and in some cases limited water resources for supporting healthy vegetation. Therefore, it is important to explore how we can reduce pavements contribution to elevated air temperatures.

UHI reduction programs aim to change three physical characteristics of neighborhoods: 1) to increase vegetation coverage, 2) to use light colored roof surfaces, green roofs, or cool roofs, and 3) to use light colored and pervious pavement types or cool pavements. The EPA (2012_a) reports that cool pavement strategies are less common than cool roof strategies. They suggest three reasons why fewer UHI reduction programs include cool pavement strategies. First, pavement surfaces must withstand considerable use and the durability and effectiveness of these surfaces changes with wear and soiling. Second, pavement temperatures are more complex than roof temperatures. Roofs are primarily affected by reflectivity. Roof heat energy is generally transferred into the interior building's air space. Whereas, pavement's heat energy is stored in the pavement, the aggregate sub-base, and underlying soils and later released. Third, unlike roofs, pavements provide multiple uses including sidewalks, stairways and ramps, parking lots, driveways, streets, and freeways. Thus cool pavement strategies require urban designers to custom design strategies to fit each context's requirements.

The Chicago Department of Transportation (CDOT) initiated the Green Alley Program (GAP) in 2006 to reduce stormwater run-off and reduce UHIs through alternative pavement design. This cool pavement program permits us with a real world opportunity to compare whether alternative pavement designs reduce air temperatures relative to nearby locations with conventional pavements. I begin with a literature review of the urban climate studies related to pavements' impact on air temperature to identify what are the most important physical properties of pavement that contribute to elevated air temperatures. Then, I describe these pavement properties for eight Chicago Neighborhoods during the summer of 2010 in addition to collecting local pavement and air temperature readings. Finally, I statistically analyze this temperature information to answer three questions. First, how do pavement temperatures impact air temperature? Second, how do alternative pavements alter the air temperature relative to conventional pavements? And finally, are alleys with the alternative pavements cooler at nighttime and in the late afternoon than alleys with conventional asphalt paving?

Literature Review

Compact urban areas often have high amounts of impervious pavements. These impervious pavements alter the surface reflectivity and energy balance and tend to produce UHIs (Stone, 2012). In this section I discuss 1) the problem with impervious pavements, 2) the physical mechanisms behind urban heat islands and how impervious pavements contribute to elevated air temperatures, 3) the differences between conventional and alternative pavements, and 4) Chicago's climate and specifics of its cool pavement program.

The large areas of impervious pavements within cities

Impervious surfaces include both buildings and pavements. Typically, the percentage of impervious surface increases with population density. In a study of 38 U.S. metropolitan regions, Imhoff and colleagues (2010) found that impervious surface covered nearly 80% of the land in compact downtown locations. Another study (Akbari et al., 2009) comparing the amount of impervious surfaces in Salt Lake City, Sacramento, Chicago, and Houston found that impervious surface covered on average 60% of the area. In those four cities in very different regions of the country, pavement covered nearly 40% of the total area while roofs covered 20 - 25%. In seven New York City neighborhoods, Rosenzweig and colleagues (2006) estimated that pavements covered 38.2 to 50.8% of the area while roofs covered 18.1 to 45%. Finally, Gray & Finster (2000) found that in 14 Chicago neighborhoods, roofs covered 29.8% to 36.9% of total area while pavement covered 18.32% to 25.62% of the area. In all of these studies, pavement was a significant impervious surface and in two of these three examples, pavement exceeded roof by area. In addition to area, Meyn & Oke (2009) found that the heat storage capacity of pavements and walls far exceeded the contribution of roofs and therefore, they concluded that pavement was an important contributor to elevated air temperature in urban environments (Meyn & Oke, 2009).

The urban heat island effect

The Urban Heat Island effect (UHI) is the warming of the atmosphere due to urban surfaces (Stewart, 2011). UHI is defined as increased air temperatures in urban areas relative to surrounding suburban and exurban areas (Solecki et al., 2005). UHIs are not the result of global climate change but changes due to global climate change are expected to exacerbate their impact (Stone, 2012). Past studies have shown that UHIs may range from 0.5^0C to as much as 12^0C and may vary by season, weather conditions, and time of day (Bonacquisti et al., 2006; Memon & Leung, 2010; Klysik & Fortuniak, 1999). In addition, UHI patterns vary by region, they occur in smaller cities as well as large cities, and they are more dispersed (or patchy) throughout metropolitan regions than once thought (Harlan et al., 2006, Bonacquisti et al., 2006; Imhoff et al., 2010; Stone, 2012; Akbari et al., 2001).

UHIs have four significant negative impacts. UHIs and high temperatures directly 1) decrease human health and well-being, 2) decrease air and water quality, 3) shorten the life cycle of infrastructure, and indirectly 4) increase energy and water use (Gartland, 2008; Memon et al. 2007; O'Neill et al, 2005, Harlan et al., 2006; Stone, 2012; EPA_d, 2012). Elevated air temperatures have the potential to not only make neighborhoods uncomfortable but they also result in deadly consequences for vulnerable residents. Heat-related deaths surpass all other natural disasters combined (NWS, 2009). Past heat waves in Europe resulted in close to 70,000 dead in 2003 and 800 dead in Chicago in 1995 (Wuebbles et al., 2010; Hayhoe et al., 2010b). Nighttime is not only the time when UHIs intensify, but past research has shown elevated nighttime temperatures are associated with higher rates of heat mortality (Kalkstein & Davis, 1989). Nighttime is a critical time when the body requires rest, without proper rest residents' are more susceptible to heat illness. Air conditioning allows residents to cope with hot temperatures (O'Neill et al., 2005). Yet, air conditioning may burden poor residents with high utility bills (Santamouris et al., 2007). In addition, air conditioning contributes to increased greenhouse gas emission. Along with automobile use, electrical generation produced using fossil fuels generates nitrogen oxide (NOx) and volatile organic compounds (VOL) emissions. When NOx and VOL interact with sunlight and heat they form ozone (Stone, 2005). High levels of ground level ozone may trigger asthma and other respiratory ailments. Finally, hot temperatures affect our critical infrastructure including the life-cycle of pavements. Pavements' life expectancy is reduced when heat melts asphalt or concrete buckles (Stone, 2012). Santero and colleagues (2011) argue that increasing the reflectivity of pavement has the potential significantly extend the life-cycle of pavement and this is overlooked when only construction costs are calculated.

Impervious pavements contribution to UHIs

Impervious pavements contribute to elevated neighborhood air temperatures by decreasing surface reflectivity (decreasing albedo), altering the surface energy balance (increasing emissivity), and reducing moisture from soil and vegetation. Albedo is the measure of the reflected shortwave radiation to incoming solar radiation. Measured from 0 - 1.0, 1.0 represents 100% complete reflection of all shortwave radiation (Santero et al., 2011). Most reflected solar radiation is not transformed into heat energy unless it is absorbed by solid surfaces. New asphalt may have an albedo as low as 0.05, absorbing up to 95% of incoming solar radiation (EPAa, 2012). In U.S. cities, urban materials absorb between 80-85% of incoming shortwave solar radiation, only reflecting 15 - to 20% of the incoming solar energy (Taha, 1997). Golden & Kaloush (2006) found on a July day in Phoenix that the difference in pavement temperature between a thick asphalt rubber pavement (with an albedo of 0.13 and surface temperature of 67^{o}C) and a thick asphalt rubber pavement painted white (with an albedo of 0.26 and a surface temperature of 51^{o}C) was 16^{o}C.

Emissivity is a ratio from 0 - 1.0 and it measures the heat energy emitted by pavements and other surfaces. An emissivity of 1.0 indicates that a material is very effective at storing heat energy and releasing it slowly. Golden & Kaloush (2006) found common conventional pavements of asphalt, concrete, and brick pavement had emissivity values over 0.90 (asphalt, 0.95-0.971; concrete, 0.90-0.98; and brick, 0.94). However, in studies of urban climate, Oke and colleagues (1991) concluded that emissivity may be less important than albedo. Oke and colleagues (1991) estimate that urban materials with an emissivity near 1.0 only altered the difference between urban and rural surface temperatures by a maximum 0.4^{o}C.

Stored heat energy from pavements is emitted in one of three forms: sensible heat, longwave radiation, and latent heat (Stone, 2012; Gartland, 2008). Sensible heat energy from pavements warms the air through convection. The rate of convection increases with higher wind speeds, with more turbulent wind patterns, and with greater temperature differences between pavements and the air (Gartland, 2008). Longwave radiation from pavements warms the air indirectly by way of a local greenhouse effect. Both sensible heat and the local greenhouse effect from pavements warm the air and contribute to UHIs (Stone, 2012). The third form of heat energy, latent heat energy, is the most desirable form to reduce UHIs because it does not result in a rise of air temperature. Unlike sensible and longwave radiation, latent heat energy is converted to an undetectable form by evaporating moisture that is transported into the upper atmosphere by water vapor (Stone, 2012). However, latent heat is dependent on the presence of moisture. Just as impervious pavements prevent air and moisture from entering soils, they also prevent moisture from leaving soils. Similarly, areas with large percentages of pavement often lack pervious planting areas where vegetation may contribute moisture through evapotranspiration.

Researchers measure UHIs in different ways. Many studies measure elevated surface temperatures using remotely sensed images or in-situ thermal infrared sensors (Voogt & Oke, 2003). Remotely sensed surface temperatures allow researchers to identify areas with elevated surface temperatures over a large continuous area (Stathopoulou & Cartalis, 2007). Yet, remotely sensed surface temperature measurements require clear skies and they are limited to the time of aerial or satellite flyover. Unlike remotely sensed images of surface temperature, in-situ infrared surface temperature measurements are not limited by cloud cover or to the limited satellite fly-over times. However, both types of surface temperature measurements are only an indirect measure of air temperatures.

The relationship between surface and air temperatures is mediated by factors such as the energy balance, roughness of the surface, wind speed, and wind direction (Stathopoulou & Cartalis, 2007: 359; Weng, 2009: 340, Weng & Quattrochi, 2006). Therefore, measurements of surface temperature may not accurately characterize the human experience of elevated air temperatures. Voogt & Oke (2003) suggest that the limitations related to surface temperature studies make fine-grained in-situ air temperature investigations necessary. Air temperatures are collected using stationary or mobile air temperature sensors. Concurrently, measuring both surface and air temperatures may be particularly useful for understanding the impact of the surface temperature of urban materials on air temperature. It is likely that urban materials' surface temperature may have a higher correlation with air temperatures under clear skies and light wind conditions (Djen et al, 1994: 2126; Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999; McPherson et al., 1997). Yet, past studies have not investigated the impact of pavement temperatures on local air temperatures under various wind conditions.

Pavements of the U.S.

The dominant pavement types in the U.S. are asphalt, concrete and modular pavers. Over time these materials have endured because of their strength, durability, and relatively low installation costs. Asphalt is used on the majority of urban roadways (53.7%) because of its relatively low initial cost and ease of installation (FHWA, 2005; Papagiannakis & Masad, 2008). Asphalt is a flexible material that conveys stress uniformly and does not need internal support (Papagiannakis & Masad, 2008). Tensile strength is a measure of the maximum strain an asphalt pavement can bear and not fracture. Tensile strength is an important physical characteristic that determines asphalts susceptibility to cracking, especially at low temperatures (Pavement Interactive, 2012). The tensile strength of asphalt should average 2,870 kilopascal (kPa) (416.26 pounds/inch^2 (psi)) for good performance particularly at low temperatures (-10^{0}C) (ASTM D6931, 2012).

Concrete is the second most common pavement material used in the U.S. Concrete is used less than asphalt largely due to its higher initial cost. Concrete is a category of materials that are rigid transmitting deflection uniformly but stress non-uniformly (Papagiannakis & Masad, 2008). This stress response is the reason why steel reinforcement is used in concrete pavements. Compressive strength is a measure of the amount of resistance a concrete pavement material can withstand under high weight loads without failure. ASTM C150 (2012), the standard specification for conventional concrete, calls for a compressive strength of 14,000 kPa (2030 psi) with a range from 17,000 kPa (2470 psi) to 21,000 kPa (3050 psi) at 28 days after installation for general use applications. Concrete is more expensive than asphalt at the time of construction but its durability may improve concretes' value relative to asphalt when life-cycle costs are considered (Rozgus, 2006).

Finally, modular pavers are made of various materials including concrete, asphalt, clay, shale, or other minerals. Pavers are generally more expensive than asphalt or concrete due to increased installation costs. Pavers may be either placed into mortar on top of a concrete or asphalt sub-base for high-volume traffic areas or placed into sand on top of an aggregate sub-base (ASTM 1272, 2012) for lower-volume areas. Concrete pavers are a common type of modular paver. The average compressive strength for individual concrete pavers is at least 55,000 kPa (8000 psi) (ASTM C936, 2012).

Alternative pavements: high albedo and permeable pavements

Two main types of cool pavement are increasingly used to reduce UHIs. One type is high albedo (highly reflective) pavement. The other type is permeable pavement that permits moisture exchange. Simulations of both high albedo and permeable pavements indicate their potential benefits reducing both surface and air temperatures. Rosenzweig and colleagues (2006) found that lightening pavement may produce the greatest reduction in air temperature of any UHI reduction strategy. Using a computer model, they determined that lightening pavements in New York City may reduce neighborhood air temperatures by as much as 2.9 ^{0}C (Rosenzweig et al., 2006). Pomerantz and colleagues (2000) estimated that lightening concrete or asphalt by 25% could result in reductions in air temperature by up to 1^0 F. Additionally, Akbari and colleagues (2001) showed that lightening pavements' albedo by 0.25 could result in cooling the pavement temperature by as much at 10^{0}C.

High albedo pavements are created by modifying conventional asphalt, concrete, and modular pavers in two general ways: 1) by incorporating light colored aggregate or pigments into the pavement material or 2) by applying a thin surface treatment. First, high albedo pavements may be constructed by incorporating light colored materials into conventional asphalt and concrete, by using resin based pavements, or by using colored asphalt and concrete (EPA_a, 2012; Mei-zhu et al., 2009). Boriboonsomsin & Reza (2010) report achieving an albedo of 0.582 for concrete replacing 70% of the cement with light colored slag (a byproduct of the steel smelting process). The second type of high albedo pavement is constructed by applying a thin surface treatment to lighten the surface of conventional concrete or asphalt. These thin treatments may include chip seals, whitetopping, ultra-thin whitetopping, and microsurfacing (EPA_a, 2012).

High albedo pavements have several limitations. First, high albedo pavements are affected by use. High albedo pavements suffer from darkening from tire wear. Levinson & Akbari (2002) found that gray-cement concretes darkened more with weathering than white-cement concretes widening the albedo difference between the two types of pavement. Gray-cement concretes had an albedo range from 0.19 to 0.50 after exposure and weathering, whereas white-cement concretes had an albedo range of 0.58 to 0.79 (Levinson & Akbari, 2002). Second, glare created by high albedo pavements may cause problems in certain locations where the increased brightness may impact drivers or pedestrian's vision. Third, depending on the heights of building and widths of streets, increased reflectivity may only displace the absorption of shortwave radiation from pavements to wall surfaces. Finally, high albedo pavements do not increase the presence of moisture in urban environments. Planners must turn to permeable pavements to increase the presence of moisture.

Permeable pavements are constructed of asphalt, concrete, or modular pavers to create surfaces that allow air and moisture to move between the atmosphere and the soil. Permeable pavements may either be 1) pervious asphalt, 2) pervious concrete, or 3) permeable modular pavers, (Scholz & Grabowiecki, 2007). Pervious asphalt contains open-graded asphalt with voids left to allow for exchange of air and water between atmosphere and soil. Pervious concrete is constructed with only large aggregate and Portland cement binder omitting the fine aggregates from the mix (Scholz & Grabowiecki, 2007). Permeable pavers themselves are impervious, but gaps with open-graded aggregate are left between pavers to allow for drainage.

The benefit of pavements with voids is that it allows cooling to occur in two ways 1) by convective cooling and 2) evaporative cooling (Greenroads, 2012). Convective cooling occurs as air is allowed to move between the cooler soil and the atmosphere through the voids in the pavements. In addition, pervious pavements have a larger surface area than conventional pavement due to the voids. This larger surface area results in increased area for contact with the air and more convection of sensible heat. Increased convection means less heat energy is stored as heat energy as compared to conventional impervious pavements. Haselbach and colleagues (2011) found that pervious concrete cooled more rapidly than conventional concrete after heat waves or peaks in daily temperature. They suggested that this makes pervious concrete a useful tool to reduce heat-illness. They also found that the heat loss from pervious concrete was enhanced with rainfall (Haselback et al., 2011). This enhancement was from evaporative cooling. Evaporative cooling is the result of moisture in the voids evaporating, converting heat energy to latent heat. Haselback and colleagues (2011) found that stormwater within the voids of pervious pavements increased heat loss from that pervious pavement over conventional pavement by as much as 13 Joules / cm^2. Nakayama and Fujita (2010) found that permeable pavements have the potential to cool air temperatures by as much as 1-2^{0}C as compared to air over conventional lawns and 3-5^{0}C as compared to air over adjacent rooftops (Nakayama & Fujita, 2010: 66).

The use of pervious pavement technologies introduces different trade-offs, primarily around durability. First, pervious pavements may not be appropriate for high traffic areas with heavy loads. Unlike high albedo pavements, adding voids changes the pavement's structural properties. Strengths of pervious pavements are directly related to the pervious pavement mixtures' coarseness, aggregate size distribution, porosity, and additives (Alam et al., 2012). Compressive strengths of pervious concretes range from 3,500 kPa to 28,000 kPa (500 psi to 4000 psi) with typical values closer to 17,000 kPa (2500 psi) (Tennis et al., 2004). A Florida Department of Transportation (FDOT, 2007) study on pervious concrete found that when balancing compressive strength with permeability, average compressive strengths were around 11,721 kPa (1700 psi). This compares to compressive strengths for general use concrete pavements of 14,000 kPa (2030 psi) (ASTM C150, 2012). Alam and colleagues (2012) found that compressive strength of pervious concrete after six years of use at an Oregon concrete mixing plant ranged from 15,580 kPa (2,259.6 psi) to 23,920 kPa (3,469.3 psi). On average pervious concrete test samples maintained a porosity of 21% (Alam et al., 2012). Pervious concrete pavement 12.7 cm. (5 in) thick with a void porosity of 20% is able to store 25 mm. (1 in.) of stormwater with 15 to 25% of the stormwater held in the concrete and 20 to 40% in the aggregate sub-base (Tennis et al, 2004). In heavy traffic areas, pervious pavements may be used between treads on narrow streets, alleys, drives, or in parking stalls because the vehicles tires are restricted to the tread portion of the pavement.

Another challenge for pervious pavement involves wear and soiling. Pervious pavements may clog within three years of installation unless well maintained (Scholz & Grabowiecki, 2007). Common causes of clogging are from traffic compressing sediment into pores, water washing sediment into pores from nearby sources, and the stress of breaking vehicles that may compress pores (Scholz & Grabowiecki, 2007). According to Scholz & Grabowiecki (2007) the lifespan of pervious pavements is directly linked to the size of the voids in the pavements. Although bigger voids result in more oxidation and less durability, bigger voids also increase moisture and air exchange thus increasing the amount of desirable latent heat and decreasing the UHI effect.

Chicago's climate

Chicago's network of freeway, street, and alley pavements provides a useful laboratory to understand the strengths and weaknesses of different cool pavement strategies relative to conventional pavements. Chicago has a continental climate of warm humid summers and cold snowy winters. Average mean temperature from May to September is 25.9^{0}C (1961-1990) (Hayhoe et al., 2010_{a}). The Chicago region lies on a flat lake plain at the southeast corner of Lake Michigan with elevations varying by only 28.6 m (94 ft.) from 176.5 m (579 ft.) to 205.1 m (673 ft.) above sea level ($USGS_{b}$, 2012). Chicago is set up on a rational street-block-alley grid system emulating from the intersection of Madison and State Streets at a latitude of 41^{0} 52' 55" North and a longitude of 087^{0} 37' 40" West ($USGS_{a}$, 2012). Extremes are common in mid-continental climates, which are marked by large swings in weather. High temperatures can reach 40.6^{0} C (105^{0}F) and lows can fall to -32.8^{0}C (-27^{0}F) (NWS Chicago Records, 2012). These temperature extremes apply significant stress to urban pavements.

In 2010, Chicago had a population density of 45.7 persons per hectare (18.5 persons per acre) (U.S. Census, 2012). Most paved surfaces are within the rights-of-way, which constitute 23% or 13,458 hectares (33,256 acres) of the City's surface area (Attarian, 2008). Within those rights-of-way 6,075 km (3,775 miles) are streets and 3,058 km (1,900 miles) are alleys. Chicago is reported to have more alleys than any other city in the world (Attarian, 2010). Alley public rights-of-way constitute about 2.4% of the city and equal 1,416 hectares (3,500 acres) in area (Attarian, 2008).

Chicago's cool pavement program

Chicago is undertaking UHI reduction because the city anticipates a rise in heat intensity and frequency (Coffee et al., 2010) will couple with UHIs to create dangerous conditions for City residents. The Chicago Department of Transportation's (CDOT) cool pavement portion of the Green Alley Program (GAP) includes the use of high albedo and permeable pavements. Attarian (2010), Project Director of the Streetscape and Sustainable Design Program at CDOT, reports that CDOT had several goals for the program. The goals were 1) to use recycled local pavement materials, 2) to balance permeability with strength of pervious pavements, 3) to lighten concretes with recycled slag, and 4) to incorporate monitoring and maintenance (see appendix E). CDOT reviewed the pavement literature, compiled best practices from around the country, designed custom pavement mixes, and conducted material testing to come up with pavement designs specifically for Chicago's requirements. The result was custom material specifications, installation techniques, and maintenance procedures that fit Chicago.

Research Questions

This study investigates how eight different pavement types impact air temperature in eight Chicago neighborhoods. Specifically I investigate three research questions. First, how do pavement temperatures impact air temperature? Based on past urban microclimate research, I expect that pavement temperatures will be explain a substantial amount of the variance in air temperature but that wind will be an important mediating variable. The second research question investigates how alternative pavements might alter air temperatures directly measured above different pavement surfaces. I expect that air temperatures over both high albedo and permeable pavements will be cooler than over conventional pavements. Finally, I investigate if alleys with the alternative pavements were cooler over longer periods of time than measured with the weather tricycle. To answer this question I examined if alleys with cool pavements were cooler on average overnight and in the late afternoon during 12 clear days than alleys with conventional asphalt paving. I expect that alleys with alternative pavements, specifically those with permeable paving, will likely be cooler than alleys with conventional pavements.

Methods

Study neighborhoods

We selected eight neighborhoods with different levels of compactness and with different cool paving strategies. I used ESRI ArcGIS 9.3 software and two (2) criteria to select neighborhoods. First, only neighborhoods with a green alley as of December 2009 were considered. Second, I reduced this number by examining green alleys that were within 1,000 feet of elevated surface temperature areas as established by a 2006 study (Chicago, 2006). I had one exception; the neighborhood of Beverly was chosen to include the only full-width pervious asphalt pavement in the Green Alley program. Beverly was not within 1,000 feet of an elevated surface temperature area. The final selected neighborhoods were East Side, Beverly, Little Italy, Bronzeville, Wicker Park, Logan Square, Austin, and Belmont Cragin (figure 5.1). Six different cool pavement strategies were represented in the selected neighborhoods including 1) one full-width pervious concrete treatment, 2) one full-width pervious asphalt treatment, 3) two high albedo pavement treatments, 4) one full-width permeable concrete pavers treatment, 5) two pervious concrete trench with conventional asphalt tread area treatment, and 6) one pervious concrete trench with high albedo concrete tread area treatment. Finally each case (green) alley was paired with a nearby control alley in the same neighborhood that had similar physical characteristics. Therefore, in eight neighborhoods, I measured16 alleys.

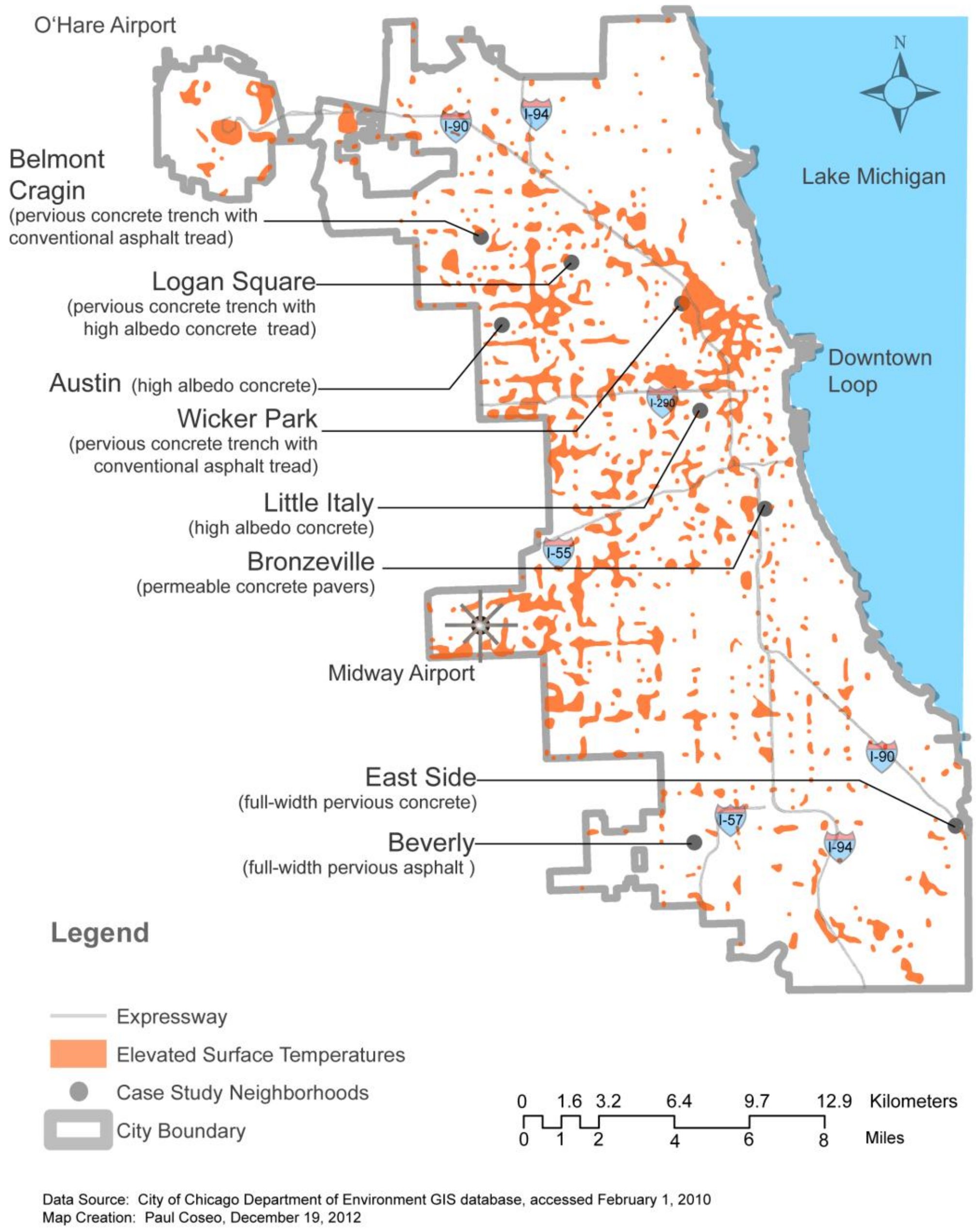

Figure 5.1: Map illustrating the city of Chicago limits, the eight study neighborhood including the green alley treatment in each case alley, and the heterogeneous distribution of elevated surface temperatures from a City of Chicago Department of the Environment 2006 study.
Data source: City of Chicago Department of Environment GIS database, accessed February 1, 2010
Illustration: by authors

Neighborhood physical characteristics and pavement types

Tables 5.1, 5.2, and 5.3 describe the sixteen neighborhood block land covers and properties including 1) block size, 2) percentage of impervious buildings and pavements, 3) alley pavement composition, and 4) pavement albedo. All but one neighborhood's case and control block area were comparable in size with average differences between case and control blocks of 1,663 m^2. However, the selected blocks in Bronzeville varied from 5,254 m^2 for the case block to 40,162 m^2 for the control block. This was part of a redevelopment project that created smaller blocks relative to Bronzeville's characteristic blocks. Percentage of the block covered by impervious surface varied from a low of 55 % for both blocks in Beverly to a high exceeding 88% in Logan Square, Little Italy, and Wicker Park. Pavement coverage varied from a low of 31.8% on the control block in Beverly to a high of 61.6% on the control block in Wicker Park. Alleys consistently covered between 3.8 to 7.0% of block area.

Although this study examined six cool pavement strategies, within each case and control alley multiple pavement types were present (table 5.2). Aged asphalt was the pavement surface in the majority of the control alleys (ranging from 95.7% to 100% of alley pavement). One control alley in Wicker Park was constructed of aged concrete. Case blocks with cool pavement strategies varied. In the East Side, Beverly, Little Italy, Bronzeville, Austin and Logan Square neighborhoods, alternative cool pavement treatments covered the entire alley. In the Wicker Park and Belmont Cragin neighborhoods only portions of the alley pavement had cool pavements. The other portions of these alleys were paved with new and aged asphalt. Also, alley driveway aprons (the ramps between the street and alley) varied in material among the neighborhoods. Alley driveway aprons were constructed of aged asphalt, aged concrete, or new concrete.

Finally, average albedo of all pavements was 0.180 ± 0.037 (table 5.3). Albedo by pavement type did not vary as much as expected with albedos of all pavements ranging from a low of 0.105 ± 0.018 for pervious asphalt to a high of 0.222 ± 0.037 for high albedo concrete. High albedo concrete had the highest range of measurements varying by 0.155 with a low of 0.135 to a high of 0.290. Note that at installation, CDOT specified the high albedo concrete to be 0.26 (Attarian, 2012).

Weather observation instruments

To measure the air temperature in each neighborhood, I took weather observations using both 1) stationary weather stations and 2) a mobile weather tricycle (figure 5.2). First, a stationary U23-002 HOBO External Temperature/RH Data Logger with sensor weather station with a model RS3 solar radiation shield was placed on a utility pole at three meter from the ground at the center of each block's back-alley. The HOBO weather stations have an accuracy of ±0.2^{0}C from 0 to 50^{0}C and relative humidity accuracy of ±2.5% from 10 to 90% relative humidity (Onset, 2010). Second, I collected mobile weather observations using a custom designed weather tricycle with micrologger that was a modified version of a cart as specified by de Dear & Brager (2001). The weather tricycle contained multiple pieces of equipment located at three meters height including a model HMP45C temperature (accuracy at 20^{0}C of ± 0.2^{0}C to ±0.3^{0}C at 40^{0}C) and relative humidity probe (accuracy at 20^{0}C of ±2% RH from 0 to 90% RH and ± 3% RH from 90% to 100% RH), model 014A wind speed sensor anemometer (accuracy of 0.11 m/s or 0.25 mph), SI-111 precision infrared radiometer (accuracy of ± 0.2°C between -10° to +65°C), and GPS16x-HVS GPS receiver (Campbell Scientific, 2012). These instruments measure the ambient air temperature, relative humidity, pavement temperature, and wind velocity respectively. Finally, an albedometer constructed of two Kipp & Zonen CMP3 Pyranometer (sensitivity between -10°C to +40°C of < 5%)(Kipp & Zonen, 2011) was used to measure pavement albedo. One pyranometer pointed up to catch incoming shortwave radiation and another pointed down to capture reflected shortwave radiation.

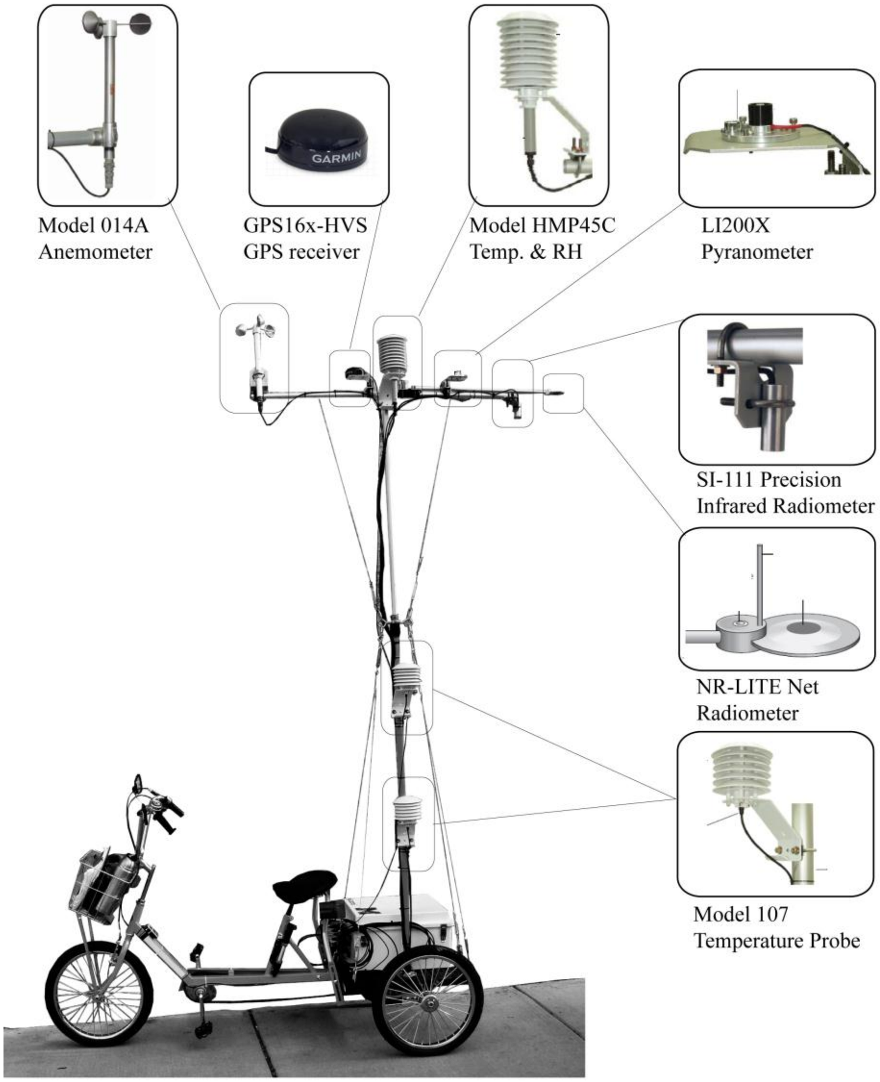

Figure 5.2: Custom designed mobile weather tricycle with equipment. Please note, only data from Model 014A Anemometer, HMP45C temperature and relative humidity probe, and SI-111 Precision infrared radiometer were used for this study.
Photograph and Illustration: by authors
Images of equipment: Campbell Scientific, 2012

Data collection procedures

We used criteria from *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites* to locate the stationary HOBO units (Oke, 2004). Each HOBO unit with solar radiation shield was screw mounted to the utility pole above the height of most truck traffic at three meters height. The data logger was also zip tied to the pole with the logger window facing upwards. A HOBO data shuttle was used to download weather observations for each data logger every two weeks and transferred to a laptop computer. Air temperature and relative humidity was measured every five minutes, 24 hours a day from July 1 to August 31, 2010 then aggregated into hourly readings for analysis. For this study, the HOBO stationary weather data is only used to show average daily temperatures for 12 clear days with light winds when UHIs are most intense (Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999; McPherson et al., 1997). The weather tricycle was deployed at 4 different times of day in each neighborhood. Observations were taken once in the early morning (7am – 9am), late morning (10am – noon), early afternoon (1pm – 3pm), and late afternoon (4pm – 6pm) over a three month period (July, August, and September 2010). Nighttime observations were excluded due to safety concerns. Air temperature, relative humidity, pavement temperature and wind speed were taken at five discrete preselected locations along the length of each case and control alley (figure 5.3).

Figure 5.3: Mobile weather tricycle collection locations 1, 2, 3, 4, and 5, typical placement along a north-south alley. East-west alleys collection location #1 was on west end of case and control alleys with #5 on east end of alleys. Not to scale, for illustration only.
Source: Bing Maps
Illustration: by authors

Quantifying neighborhood physical characteristics:

Past research has shown that the percentage of impervious surfaces, percentage of tree canopy, percentage of roofs, percentage of pavements, and pavement albedo influence surface and air temperatures (Stone, 2012: Alberti, 2009; Gartland, 2008; Akbari et al., 2001; Imhoff et al., 2010; Yuan & Bauer, 2007; Kuttler et al., 1996; Zhou et al., 2011). To calculate land cover percentages for each of the 16 blocks, I used high resolution orthoimagery from April 9, 2010 (http://earthexplorer.usgs.gov/). Impervious surfaces, roofs, and pavements were calculated using a similar method to Akbari and colleagues (2003). This procedure included calculating impervious surfaces beneath the tree canopy. Block calculations for impervious surface and tree canopy included the entire block extending out from street curb to the midpoint of each of the four bounding streets. Tree canopy was calculated to include only deciduous shade and coniferous trees omitting herbaceous cover. Pavement albedo was measured using an albedometer at waist height or 1.1 m. (3 ft. 7 - 5⁄16 in.) on clear days within two hours of solar noon.

Table 5.1:

Descriptive Statistics of Case and Control Block Land Cover, Variables Used in the Analysis for Eight Chicago Neighborhoods in Summer 2010

Neighborhood	Alley	Block Area	Impervious Surface Area	Land Cover of Each Block		% Roof Cover and Pavement Cover of Total Block Area		% Street, Alley, and Other Pavements of Total Block Area		
		m^2	m^2	% Impervious	% Tree Canopy	% Roof Cover	% Total Pavement	% Street Pavement	% Alley Pavement	% Other Pavement
Bronzeville	Case*	5,254	4,240	80.7	2	33.4	47.2	21.4	6.9	19
	Control	40,162	32,086	79.9	18.5	21.8	58.1	16.9	4.4	36.8
Little Italy	Case	19,725	17,455	88.5	21.7	38.4	50	18.2	4.4	27.4
	Control	20,604	19,436	94.3	29.4	39.1	55.2	17.3	4.3	33.7
Austin	Case	19,968	16,779	84	18.5	33.2	50.9	13.6	4.6	32.7
	Control	19,794	14,873	75.1	19.7	28.2	46.9	14.4	4.2	28.4
Belmont Cragin	Case	25,650	19,500	76	17.1	34.9	41.1	12.9	4.6	23.6
	Control	23,219	18,104	78	18.1	37.9	40.1	13.2	4.1	22.7
Wicker Park	Case	15,592	15,144	97.1	12.8	40.8	56.3	20.9	6.8	28.6
	Control	13,462	12,879	95.7	4.7	34	61.6	25	6.3	30.4
Beverly	Case	23,018	12,574	54.6	54.6	20.9	33.7	14.1	4.1	15.5
	Control	22,678	12,391	54.6	60.4	22.9	31.8	11.5	4.6	15.6
East Side	Case	18,816	14,198	75.5	19.4	30.2	45.2	16.5	3.8	24.9
	Control	19,468	14,325	73.6	23.1	31.9	41.7	14.4	3.8	23.5
Logan Square	Case	30,852	27,817	90.2	6.6	36.8	53.4	19.3	6.5	27.6
	Control	25,821	22,739	88.1	13.2	37.9	50.1	16.8	7	26.3
Average	All blocks	21,505	17,159	80.4	21.2	32.6	47.7	16.6	5	26

*Bronzeville case block is part of a Hope VI redevelopment

Table 5.2:
Descriptive Statistics of Alley Pavements by Case and Control Alley, Variables Used in the Analysis for Eight Chicago Neighborhoods in Summer 2010

Neighborhood	Alley	Area		% of Alley Composed of Conventional Pavement Types				% of Alley Composed of Alternative Cool Pavement Types			
		Impervious m^2	Alley m^2	% Aged Asphalt	% New Asphalt	% Aged Concrete	% New Concrete	% High Albedo Concrete	% Pavers	% Pervious Concrete	% Pervious Asphalt
Bronzeville	Case	4,240	362	-	-	-	-	14.5	85.5	-	-
	Control	32,086	1,787	98.7	-	1.3	-	-	-	-	-
Little Italy	Case	17,455	873	-	-	-	-	100.0	-	-	-
	Control	19,436	881	96.4	-	3.6	-	-	-	-	-
Austin	Case	16,779	919	1.4	-	-	-	98.6	-	-	-
	Control	14,873	822	100.0	-	-	-	-	-	-	-
Belmont Cragin	Case	19,500	1,176	63.2	30.2	-	-	2.5	-	4.1	-
	Control	18,104	957	96.7	-	3.3	-	-	-	-	-
Wicker Park	Case	15,144	1,062	61.8	26.8	-	3.5	-	-	7.9	-
	Control	12,879	843	2.6	-	95.7	1.6	-	-	-	-
Beverly	Case	12,574	942	-	-	-	7.3	-	-	-	92.7
	Control	12,391	1,049	95.7	4.3	-	-	-	-	-	-
East Side	Case	14,198	718	-	-	-	4.9	-	-	95.1	-
	Control	14,325	737	97.2	-	2.8	-	-	-	-	-
Logan Square	Case	27,817	2,001	-	-	-	-	97.6	-	2.4	-
	Control	22,739	1,820	100.0	-	-	-	-	-	-	-

Table 5.3: Average Albedo by Pavement Type for all Case and Control Alley Pavements

Pavement Type	Samples	Average Albedo	Std. Dev.	Minimum	Maximum
Aged Asphalt	140	0.168	0.015	0.132	0.202
New Asphalt	8	0.136	0.004	0.132	0.139
Aged Concrete	31	0.207	0.017	0.186	0.227
New Concrete	11	0.213	0.022	0.188	0.237
High Albedo Concrete	64	0.222	0.037	0.135	0.290
Concrete Pavers	16	0.166	0.010	0.149	0.176
Pervious Concrete	24	0.159	0.013	0.137	0.180
Pervious Asphalt	16	0.105	0.018	0.085	0.122

Results

We collected data during a period when the daily average air temperature at Midway Airport of 25.45^{0}C was slightly below the summer's statistical average of 25.9^{0}C (1961-1990) (Hayhoe et al., 2010a). However, from July 2 to August 16, 2010 Chicago witnessed an all-time record of 46 consecutive days with highs over 80^{0}F (26.7^{0}C) (NWS Chicago, 2010). During the months of July and August Chicago experienced four heat waves (two days or more with consecutive highs above 32.2^{0}C (90^{0}F)) or 12 heat event days total (Sheridan, 2012).

First, I wanted to understand the relationship between pavement and air temperatures. I ran a bivariate regression model with air temperature at three meters as the dependent variable and pavement temperature as the independent variable (table 5.4). Both measurements were made from the weather tricycle simultaneously. For all observations, the model explains 66 % of the variance in air temperature at three meters. Yet, past research has shown that surface temperatures contribute more to elevated air temperatures under light wind speeds (Oke, 1987; Klysik & Fortuniak, 1999). So to understand the impact of wind speed, I divided the recorded six minute averaged wind speeds at three meters into quartiles at the 25th, 50th, 75th, 100th percentile. On the days I collected data using the weather tricycle, the 25th percentiles were those six minute averaged wind speeds less than 1.21 m/s (2.71 mph). The 50th percentiles were those wind speeds less than 1.65 m/s (3.69 mph). The 75th percentiles were those wind speeds less than 2.28 m/s (5.10 mph). The 100th percentiles were all winds speeds collected. The highest wind speed collected was 5.39 m/s (12.06 mph). I then selected out each percentile group with corresponding air temperatures and reran the bivariate regression of air temperature as the dependent variable and pavement temperature as the independent variable. When I controlled for wind speed, the correlation between pavement and air temperatures increased. Pavement temperatures increased from explaining 66% (n = 310) of the variance in air temperatures for all wind speeds to explaining 84% (n = 75) of the variance in air temperatures for the lowest wind speeds. This finding indicates that pavement temperature can have a large impact on air temperature especially under light wind conditions. Over the two month period winds were lightest at night at Midway Airport and therefore, pavement temperatures are more likely to influence nighttime air temperatures because of lower nighttime wind speeds.

Table 5.4:
Bivariate Regression Air Temperature (dependent variable) on Pavement Temperature (independent variable) at three meters with Decreasing Wind Speeds from Weather Tricycle

Wind speed	*m/s*		*B*		*SE*	*Beta*
Lowest wind speeds 25% percentile	< 1.21	Pavement temperature	0.60***		0.03	0.92
		(Constant)	9.39***		0.87	
		n= 75				
		Adjusted R2 = 0.84***				
50% percentile of wind speeds	< 1.65	Pavement temperature	0.48***		0.02	0.88
		(Constant)	12.47***		0.70	
		n= 153				
		Adjusted R2 = 0.76***				
75% percentile of wind speeds	< 2.28	Pavement temperature	0.41***		0.02	0.82
		(Constant)	14.84***		0.63	
		n= 232				
		Adjusted R2 = 0.68***				
All wind speeds 100% percentile	< 5.39	Pavement temperature	0.39***		0.02	0.81
		(Constant)	15.40***		0.57	
		n = 310		310		
		Adjusted R2 = 0.66***		0.66		

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Next, I used a linear mixed model approach to understand if pavement type influenced air temperatures (collected at three meters on the tricycle). Mixed models or varying-intercept models are good for data that needs to be structured in groups for analysis (Gelman & Hill, 2007). First, I paired case and control alley locations to understand how a pavement material in relatively equivalent alley locations influenced air temperature.

The linear mixed model approach provided good results in understanding how the time of day, pavement type, and location on the alley influenced air temperature at three meters. Pairing cool pavements with a conventional pavement provided us with the following model of pavements' effect on air temperatures at three meters.

$T_a = b_o + b_1D_1 + b_2D_2 + b_3D_3 + b_4PM_2 + b_5 PM_3 + b_6 PM_4 + b_7 PM_5 + b_8 PM_6 + b_9 PM_7 + b_{10} PM_8 + e$

<u>Dependent Variable:</u>
T_a = air temperature at three meters,
<u>Independent Variables:</u>
D_1 = early morning
D_2 = late morning
D_3= early afternoon
D_4= late afternoon
PM_1 = aged asphalt
PM_2= new high albedo concrete (1-5 years)
PM_3 = new asphalt (1-5 years)
PM_4 = pervious concrete
PM_5 = concrete pavers
PM_6 = new concrete (1-5 years)
PM_7 = aged concrete
PM_8 = pervious asphalt

Where T_a represents air temperature at three meters, D represents diurnal time of day (early morning, late morning, early afternoon, and late afternoon) and PM represents the eight pavement types (aged asphalt, new asphalt (1-5 years), aged concrete, new concrete (1-5 years), new high albedo concrete (1-5 years), concrete pavers, pervious concrete, and pervious asphalt) I sampled in all 16 alleys. In addition, the model uses early morning (b_1D_1) and aged asphalt pavements (b_{12} PM_1) as controls for analysis, thus they are zero (0) in the equation below (table 5.5).

$T_a = 24.46 + 4.26D_2 + 6.56D_3 + 7.83D_4 - 0.61 PM_2 - 0.84 PM_3 - 0.40 PM_4 + 0.52 PM_5 - 0.47 PM_6 - 0.20 PM_7 - 0.10 PM_8 + e$

Table 5.5:
Mixed Linear Model Air Temperature (dependent variable) on Pavement Type (independent variable) Controlling for Location and Time of Day at Three Meters on the Weather Tricycle

		Mixed Linear Model		
Variable	*n*	*B*	*SE*	*Sig.*
Early morning		0a	0	
Late morning		4.26	1.39	0.005
Early afternoon		6.56	1.39	0.000
Late afternoon		7.83	1.44	0.000
Aged Asphalt	140	0a	0	
New High Albedo Concrete	64	-0.61	0.14	0.000
New Asphalt	8	-0.84	0.31	0.007
Pervious Concrete	24	-0.40	0.20	0.047
Concrete Pavers	16	0.52	0.26	0.051
New Concrete	11	-0.47	0.27	0.079
Aged Concrete	31	-0.20	0.18	0.270
Pervious Asphalt	16	-0.10	0.27	0.698
Constant		24.46	0.99	0.000

a. This parameter is set to zero because it is redundant.

The overall model is significant with an F value of 5.09 for the effect of pavement type on air temperature at comparable alley locations. In addition, time of day's effect on air temperature for comparable alley locations is significant with an F value of 11.76. The negative coefficients indicate air temperatures cooler than air temperatures over aged asphalt samples.

High albedo pavements (PM_2, n = 64) were the most significant pavement type in reducing air temperature when compared to other pavements in equivalent locations in control alleys. We would expect summertime (July - September) air temperature in comparably oriented Chicago alleys with similar block characteristics at three meters to be 0.61^0 C $\pm 0.14^0$ C (1.1^0F) cooler over new high albedo concrete pavements when compared to aged asphalts. Permeable pavements (PM_4, n = 24) were more variable in their impact on air temperature compared to aged asphalts. Air temperatures over pervious concretes were 0.40^0 C $\pm 0.20^0$ C ($p < 0.05$ level) cooler than air temperatures over aged asphalts. Therefore, permeable concrete was comparable with high albedo concrete pavements in reducing air temperatures. Pervious asphalts (PM_8, n = 16) were not significant in cooling relative to conventional aged asphalt. The last cool paving technique, concrete pavers (PM_5, n = 16) actually showed a warming effect of $+0.51^0$ C as compared to air temperatures over aged non-pervious asphalts. The concrete pavers were dark red with a measured albedo of 0.17 similar to that of the measured albedo of aged asphalt (0.17). This may have contributed to the warming effect (table 5.3). Other pavements, including aged and new conventional concrete were not found to be significant in predicting air temperature at three meters. New asphalt (PM_3, n = 8) was significant, resulting in cooler air temperature of 0.84^0 C when compared to a similar location over aged non-pervious asphalt sample. Yet, it had a small sample size (n = 8) so it should be interpreted with caution. In this case, all new asphalt samples were located in case alleys in Belmont Cragin and Wicker Park at location three (mid-alley) and five (end of alley) respectively, which were fairly shady locations.

Finally, I wanted to understand if cool pavements had cooling benefits over longer periods of time. I conducted a paired t-test using the stationary HOBO weather station data to understand if case air temperatures in the alleys with the cool pavement strategies were significantly cooler on average over 12 clear than paired control air temperatures. I chose two important times of day. I investigated at night (2 a.m.) and during the day (4 p.m.) during clear days in July and August, 2010. Past research has shown that UHIs are more likely to develop during clear skies and light winds (Djen et al, 1994: 2126; Stewart, 2011; Bonacquisti et al., 2006; Gedzelman et al., 2003; Kim & Baik, 2002; Klysik & Fortuniak, 1999), but also that high temperatures at night likely increase heat mortality (Kalkstein & Davis, 1989). During the two-month period, only12 days had clear skies. The results of the analysis were mixed at both 2 a.m. (table 5.6) and 4 p.m. (table 5.7). While some case alley air temperatures were significantly cooler than the paired control alley air temperature, other case alley air temperatures were significantly warmer. From the paired t-test analysis I found no discernible pattern in the longer term cooling ability of case alleys with alternative pavements over the control alleys with conventional pavements. The pavement design with a consistent cooling was the pervious concrete trench with conventional asphalt treads. Wicker Park's case alley was significantly cooler than its control alley by -

0.16^{0}C at 2 a.m., but its case alley was significantly warmer than the control alley at 4 p.m. Belmont Cragin's case alley with a similar alternative pavement design as Wicker Park's case alley had an insignificant difference in mean air temperature at 2 a.m., but its case alley was significantly cooler than the control alley by -0.35^{0}C at 4 p.m. These mixed results make it difficult to discern any longer term pattern from alternative pavement designs on mean air temperatures at 2 a.m. and 4 p.m. collected from the stationary HOBO weather stations.

Table 5.6:
Means, standard deviation, and paired t-tests for air temperature during 12 clear days at 2 a.m.

Neighborhood	Alley	Pavement Type	Mean Air Temperature C	Std. Dev.	Case - Control Difference	Paired t-test	Sig.
Austin	Case	High Albedo Concrete	21.44	2.92	-0.28	-3.835	0.003
	Control	Aged Asphalt	21.71	2.93			
Wicker Park	Case	Pervious Concrete Trench with Conventional Asphalt	23.05	2.76	-0.16	-2.766	0.018
	Control	Aged Concrete	23.21	2.64			
Logan Square	Case	Pervious Concrete Trench with High Albedo Concrete	22.52	2.89	-0.09	-1.713	0.115
	Control	Aged Asphalt	22.61	2.80			
Belmont Cragin	Case	Pervious Concrete Trench with Conventional Asphalt	21.63	2.97	0.04	1.431	0.180
	Control	Aged Asphalt	21.59	3.00			
Bronzeville	Case	Permeable Pavers	22.42	2.77	0.13	1.346	0.205
	Control	Aged Asphalt	22.28	2.70			
East Side	Case	Pervious Concrete	21.43	2.38	0.14	3.387	0.006
	Control	Aged Asphalt	21.28	21.28			
Little Italy	Case	High Albedo Concrete	23.16	2.70	0.22	5.135	0.000
	Control	Aged Asphalt	22.94	2.71			
Beverly	Case	Pervious Asphalt	19.95	3.12	0.89	3.185	0.009
	Control	Aged Asphalt	19.06	2.88			

Table 5.7:
Means, standard deviation, and paired t-tests for air temperature during 12 clear days at 4 p.m.

Neighborhood	Alley	Pavement Type	Mean Air Temperature C	Std. Dev.	Case-Control Difference	Paired t-test	Sig.
Belmont Cragin	Case	Pervious Concrete Trench with Conventional Asphalt	31.70	2.88	-0.35	-4.045	0.002
	Control	Aged Asphalt	32.05	3.04			
Logan Square	Case	Pervious Concrete Trench with High Albedo Concrete	31.45	3.04	-0.13	-0.763	0.461
	Control	Aged Asphalt	31.58	2.71			
Austin	Case	High Albedo Concrete	31.26	2.89	0.07	0.467	0.650
	Control	Aged Asphalt	31.19	2.56			
Bronzeville	Case	Permeable Pavers	31.38	3.21	0.26	2.332	0.040
	Control	Aged Asphalt	31.12	3.07			
East Side	Case	Pervious Concrete	31.46	3.52	0.33	2.431	0.033
	Control	Aged Asphalt	31.12	3.55			
Beverly	Case	Pervious Asphalt	29.89	2.98	0.69	1.235	0.243
	Control	Aged Asphalt	29.19	3.77			
Little Italy	Case	High Albedo Concrete	31.96	3.38	1.04	8.551	0.000
	Control	Aged Asphalt	30.92	3.26			
Wicker Park	Case	Pervious Concrete Trench with Conventional Asphalt	31.87	3.48	1.18	6.225	0.000
	Control	Aged Concrete	30.69	3.15			

Conclusions

The analysis shows evidence that alternative cool pavements strategies such as high albedo concrete and pervious concrete are useful in reducing air temperature at three meters. The main findings suggest 1) the relationship between pavement temperature and air temperature changes under different wind conditions, 2) some alternative pavements provide a greater cooling effect over conventional pavements, and 3) longer term nighttime and daytime cooling benefits of alternative pavement designs are mixed. These findings point to important benefits and limitations of alternative pavement designs that planners should consider when drafting cool pavement programs.

First, the findings suggest that surface temperatures are not a perfect surrogate for air temperatures. Under light winds conditions pavement temperature was shown to explain up to 84.3% of the variance in air temperature. Yet, as wind speeds increase the relationship decreases. Although surface temperature measurements under light wind conditions may provide a good proxy for air temperatures, measuring surface temperatures under strong winds should be avoided. Under stronger winds it is likely that adjacent upwind sources of heat may be more influential on local air temperatures than local pavement temperatures. In addition, this finding indicates the usefulness of mobile weather observations to discern the fine scale impacts that pavement temperature has on air temperature. The findings suggest that pavement temperature plays an important role in warming air temperatures directly above pavements under light wind conditions.

Second, the mixed linear model analysis suggests that both high albedo pavements and pervious concrete pavements were most significant in reducing air temperatures. I found that air temperatures over high albedo concrete at three meters were 0.61^{0} C (1.1^{0}F) cooler than air temperatures over aged asphalt pavement samples in similar alley locations. I choose to look at pavement material as a factor in predicting air temperature as opposed to albedo because the albedo readings were likely overestimates due to the high reflectivity in the alleys (Erell et al. 2010). This is especially problematic in alleys due to the presence of garages with many white or light colored doors. Yet, the findings of cooler air temperature measured over high albedo concrete generally align with previous research simulating the cooling effect of high albedo surfaces (Pomerantz et al., 2000). Pomerantz and colleagues (2000) estimated that that if pavement albedo was raised to decrease the absorption of shortwave radiation by 90% to 65%, maximum daily air temperatures on hot August days could be reduced by as much as 0.6°C (1°F). The findings support this estimate. Pervious concrete samples provided 0.40^{0} C reductions in air temperature as compared to air temperature over aged asphalt pavement samples. Although not as much cooling resulted from pervious surfaces as estimated by Nakayama & Fuijita (2010) model (1-2^{0}C over lawn and 3-5^{0}C over rooftops), some cooling was still found. Other alternative pavement material types such as pervious asphalt and concrete pavers were not significant in reducing air temperatures as compared to the aged asphalt. The weather tricycle analysis was only a snap shot of air temperatures over cool pavements; I also wanted to understand cool pavements' effect over longer periods of time.

Finally, over longer periods of time permeable pavements showed the most promise of cooling average air temperatures over 12 clear days in summer 2010 at 2 a.m. and 4 p.m. over conventional pavements. Although the results were mixed, the paired t-tests showed that the only alternative pavement design with a consistent cooling effect was the pervious concrete trench with conventional asphalt pavement. The case alleys in both Wicker Park and Belmont Cragin had this pavement treatment. Wicker Park's case alley was significantly cooler than its control alley by -0.16^{0}C at 2 a.m. This compares to Belmont Cragin's case alley, which was significantly cooler than the control alley by -0.35^{0}C at 4 p.m. The cooling may have resulted from both increased convective cooling from the larger surface area of the pervious concrete and the additional moisture available from the trench (Haselback et al., 2011; Greenroads, 2012). Yet, the analysis from the paired t-test suggests that although the analysis from a stationary weather station provides longitudinal data, it has some limitations when trying to discern small impacts of pavement temperatures on air temperatures. The longitudinal data is limited by its stationary position at the center of the alley. It may not be able to pick up finer scale fluxuations in air temperature as mobile weather observations.

In-situ evaluation of cool paving programs is necessary to monitor how changes to the physical properties of pavement impact air temperatures. The findings suggest two implications for UHI analysis. First, from the weather tricycle I found that alley pavement temperatures explained a substantial amount of the variance in air temperatures especially under light wind conditions. Under light winds cool pavement strategies have the potential to produce the most desirable impacts on local air temperatures. However, as wind speeds increase other physical factors likely contribute to local alley air temperatures. Second, I found evidence that supports the cooling benefits of both high albedo and pervious concrete pavements. I found that air over high albedo and pervious concrete was cooler when compared to air over aged asphalt in comparable alley locations. Yet the research does not address a potential troubling aspect for cool paving strategies for the potential of high albedo pavements to simply displace reflected radiation into building walls. This might be especially true in some cities, such as Chicago, with many dark bricked buildings. The advancement of three dimensional analyses, which include wall areas will help better articulate this complex relationship.

The findings suggest three implications for UHI reduction programs. First, reducing pavement temperatures will likely reduce air temperatures, especially under light wind conditions that often occur at night. Cool pavements may be less useful under windy conditions that displace air from upwind locations. Second, both high albedo concrete and pervious concrete show evidence of providing air temperature reductions over conventional pavement materials. Third, pervious concretes may provide longer term nighttime and daytime cooling benefits than other strategies. Yet, the results were mixed. I found in Wicker Park's and Belmont Cragin's case alleys with pervious concrete trenches provided cooling at one time of day, while warming at another. More research is required into the long-term average benefits of cool pavement technologies. Although many studies have called for the use of high albedo pavements (Rosenzweig et al., 2006; Akbari et al., 2001; Pomerantz et al., 2000) to reduce air temperatures, less studied is the use of permeable pavements to reduce air temperatures (Haselback et al., 2011; Nakayama & Fujita, 2010). Future versions of the U.S. Green Building Council's LEED rating system should provide UHI reduction credits for permeable pavements. The findings suggest further support for the cooling benefits of using permeable concretes (Haselback et al., 2011; Nakayama & Fujita, 2010). This finding is especially important in cities that are trying to tackle both UHI reduction and stormwater management. The co-benefits of permeable pavements are that they may be able to reduce both in elevated air temperatures and flooding.

6.1 Limitations:

The study has at least four limitations. First, the analysis was limited by large differences in pavement sample size due to using real world design installations. Aged asphalt and high albedo concrete had the highest sample size at 140 and 64 samples respectively, whereas new asphalt had only eight samples. Second, the analysis was limited to the condition of pavement present in the 16 case and control alleys. Use by residents likely varies, especially relative to density. Use of the alley is likely more intense in higher density neighborhoods such as Wicker Park than lower density neighborhoods such as Beverly. Alley use and wear may impact performance of high albedo and permeable pavement types. Second, mobile weather observation is subject to time limitations of the transverse. Each alley transverse took roughly one hour, but it was longer at times due to vehicles or residents stopping the weather tricycle to ask questions about the research. Over this time period small changes to atmospheric conditions may have occurred. Finally, the stationary weather observations provided good information about daily long-term air temperature fluxuations but were less helpful in understanding smaller scale features of the alley climate environment.

Chapter 6

Conclusion

As our cities warm over the next century, evaluating neighborhood environments for urban heat island analysis and reduction programs will become a critical piece of environmental planning's ethical obligation to "… promote excellence of design and endeavor to conserve and preserve the integrity and heritage of the natural and built environment" (APA, 2012). As researchers, we must provide practitioners with 1) information on how physical characteristics of neighborhoods differentially contribute to UHIs, 2) guidance regarding the level of accuracy in land cover characterization required to predict local UHIs, and 3) evaluations of in-situ UHI reduction strategies.

As UHIs worsen and the number and frequency of extreme heat events expand with global climate change, neighborhood climate evaluation is becoming a critical planning tool for planning intervention strategies. Some cities are implementing UHI reduction programs to address heat vulnerability in a warming world and many cities are embedding these within Climate Action Plans (Stone, 2012). Currently, UHI reduction strategies focus on alternative roof and pavement materials as well as increasing the urban tree canopy. This dissertation is intended as a guide for researchers and planners on how to evaluate neighborhood environments for UHI reduction programs.

This dissertation research addresses three main gaps in the literature for UHI research at the intersection of urban design, urban climatology/meteorology, and public health. First, chapter three addresses the lack of guidance in the current research for the relative contribution of physical characteristics to elevated air temperatures. The intent of this article is to provide researchers and planners guidance on what physical characteristics they should prioritize to reduce neighborhood UHIs. This chapter also demonstrates how neighborhood physical characteristics differ in their influence by time of day and during extreme heat events.

Specifically, in this chapter I found that percent impervious surface (.82 at 2 a.m.), percent tree canopy (-.72 at 2 a.m.), and distance to industrial areas (-.52, at 4 p.m.) had the highest bivariate correlations with elevated air temperatures in the eight Chicago neighborhoods. Yet, this varied by time of day and with weather conditions. At 2 a.m. on 12 clear days the model had more explanatory power (adjusted R^2 =0.68, at 2 a.m.) than at 4 p.m. (adjusted R^2 =0.26). At 2 a.m. percent impervious surface was the most significant predictor of nighttime elevated air temperatures. On the 12 clear days during the late afternoon (4 p.m.) distance to industry was the most significant predictor of elevated afternoon air temperatures in the eight Chicago neighborhoods. When I reran the 2 a.m. and 4 p.m. UHI models during two heat event days, I found that the model's explanatory power increased at 2 a.m. (adjusted R^2 =0.90) and decreased in explanatory power at 4 p.m. (adjusted R^2 =0.12). During the two heat event days at night (2 a.m.) both percent impervious and percent tree canopy were significant predictors of elevated air temperatures. At 4 p.m. on the two heat event days no predictors were significant. In general, it was more difficult to predict elevated afternoon air temperatures than elevated nighttime air temperatures. This is similar to what Zhang and colleagues (2011) found in a study of 17 sites in metro Detroit. They found that percent impervious surface was a significant predictor of elevated air temperatures at night, but not during the afternoon.

Another important factor in measuring UHIs is wind. Wind speeds at Midway Airport were lighter at night than in the late afternoon. Increased wind speeds likely expanded the area of influence on air temperatures and upwind locations, such as distance to industry, became more influential as winds increased. With lighter winds at night the urban-induced heating was more influenced by the local physical characteristics, so percent impervious and percent tree canopy of the block became more important. Past urban meteorology research presents conflicting information on how compact neighborhood building configuration contributes to elevated air temperatures. Some researchers claim that neighborhood building configuration plays a significant role in driving neighborhood air temperatures (Eliasson, 1996; Svensson, 2004; Oke, 2004; Oke et al., 1991; Sakakibara, 1996). Other research (Stone, 2012; Stone et al., 2007; Stone

& Norman, 2006) claim other factors such as land cover play a more significant role than building configuration. The findings suggest researchers and planners should prioritize land cover factors of impervious surface and tree canopy to predict neighborhood UHIs in urban areas similar to Chicago over building configuration and street orientation. I found that these land cover factors are likely the most significant drivers of air temperatures in the eight Chicago neighborhoods relative to neighborhood building configuration and adjacent heat sources and sinks factors. Land cover variables are significantly less difficult to measure relative to other factors that I explored and this has practical implications for future work.

Second, chapter four explores different approaches to land cover quantification. Past UHI research has primarily used two dimensional approaches to quantify land cover variables but research by Akabari and colleagues (2003) has seriously questioned the precision of this approach. While the three-dimensional approach is more accurate, this more laborious process does not significantly improve the explanatory power of UHI models. I found that the three-dimensional approach may be more important for certain types of neighborhoods, specifically medium-high density neighborhoods with moderate to high amounts of tree canopy. I found that calculating the impervious surface area under the neighborhood's 29.4% tree canopy coverage in Little Italy improved the description of impervious surfaces. By documenting the area under the tree canopy I found an additional +27.8% of impervious surface area. Taking a three-dimensional approach and documenting impervious surfaces is not as critical for roofs, alleys, or in neighborhoods with low percentages of tree canopies (4.7% tree canopy) such as Wicker Park.

Nonetheless, I found that using the more accurate documentation of impervious surfaces did not substantially change the UHI model at 2 a.m. or 4 p.m. In addition, it did not affect the significant predictors. Percent impervious, tree canopy, and distance to industry remained the most significant predictors of elevated air temperatures. I found that although a three-dimensional approach improved the description of land cover overall, planners may reasonably use the more coarse two-dimensional approaches when quantifying land cover variables to predict elevated air temperatures. The findings may also suggest the important role that trees play in reflecting, absorbing, and diffusing incoming sunlight so as to shade impervious surfaces below tree canopies.

Finally, chapter five evaluates cool pavement performance. Much of this research is based on computer simulations and generally lacks in-situ evaluations. In addition, past research has not examined the impact of pavement temperature's impact on air temperatures under various wind speeds. Using the weather tricycle I found that under light wind conditions pavement temperature explained over 80% of the variance in air temperatures. As wind speeds increased the relationship decreased. Again this provides more evidence of the localized effects of urban materials under light winds and as wind speeds increase it is likely that the area of influence increases. Cool pavements may have the biggest impact in reducing air temperatures under light wind conditions that often occur at night. In addition, I found evidence that highly reflective and pervious concretes provide in-situ cooling benefits. Air measured at three meters with the weather tricycle over highly reflective concrete was -0.61^{0}C cooler than comparable aged asphalt pavements. Similarly, air temperature at three meters over pervious concrete was -0.40 ^{0}C cooler than comparable aged asphalt pavements.

Yet, I found mixed results on the cooling benefits of cool pavement strategies when I examined the pavements with stationary weather stations over a longer period of time (12 clear days) at 2 a.m. and 4 p.m. The pavement type that provided the most consistent cooling was a pervious concrete trench with asphalt tread. In Wicker Park the pervious concrete trench was significantly cooler (by -0.16^{0}C) than the control aged concrete paved alley at 2 a.m. Yet, at 4 p.m. the pervious concrete trench in Wicker Park was significantly warmer than the control alley. The pervious concrete trench in Belmont Cragin was not significantly different than the control aged asphalt alley at 2 a.m., but significantly cooler (by -0.35^{0}C) than the base course condition of the control alley at 4 p.m. These mixed results show more research is needed into the longer-term effects of in-situ cool pavement performance.

In terms of UHI reduction programs, the findings suggest several implications related to changing urban climates. From the research in eight Chicago neighborhoods I found the most influential categories on the UHIs were land cover factors (percent impervious surface and tree canopy) at night and adjacent heat sources and sinks (distance to industry) during the day. The findings suggest that evaluating and predicting neighborhood air temperatures is more localized at night under light winds. In the afternoon wind speeds increase displacing air temperatures from upwind locations and likely enlarging the area of examination. In addition, I found that building configuration at the neighborhood scale was not a significant predictor of air temperature at night. This provides further evidence that other factors such as impervious surface, tree canopy, and distance to heat sources such as industrial areas contribute more to warm microclimates than compact building configurations in cities such as Chicago.

In chapter four, I found that two-dimensional approaches are adequate for planners to predict neighborhood elevated air temperatures. The only exception to the recommendation involves medium to high density neighborhoods with significant amounts of tree canopy. I found in Little Italy (a medium to high density neighborhood with 95% impervious surfaces and 30% tree canopy) that documenting impervious surfaces under tree canopies resulted in increasing the documented amount of impervious surfaces by roughly 25% over a two-dimensional approach. Although highly detailed quantification of land cover is not necessary for UHI prediction, more accurate and detailed three-dimensional quantifications of land covers are useful for urban forestry and rights-of-way planning.

In chapter five, the findings suggest cool pavements reduce elevated nighttime air temperatures. I found that pavement temperatures were more influential on local air temperature under light winds. Light winds more commonly occur at night, making cool pavements more influential to reduce nighttime air temperatures. However, nighttime is also a critical time of day for human well-being. I found the most useful cool pavements to reduce air temperatures were 1) highly reflective concrete and 2) pervious concrete. I measured air temperatures at least -0.40^{o}C cooler over both highly reflective concrete and pervious concrete pavements when compared to air temperatures over conventional impervious asphalt pavements. Yet, I also found that longer term cooling effects were mixed and more longitudinal research is needed. While many past studies have provided evidence and advocated for the use of highly reflective pavements (Rosenzweig et al., 2006; Akbari et al., 2001; Pomerantz et al., 2000) for UHI reduction, fewer studies have provided evidence and advocated for the use of permeable pavements (Haselback et al., 2011; Nakayama & Fujita, 2010). Introducing moisture into the air may be an important UHI mitigation strategy that pervious pavement provide. LEED currently does not provide credits for permeable pavements to reduce UHIs. Environmental credit systems, such as LEED, should add permeable pavements as an effective strategy to reduce UHIs. Although vegetation is preferable to pavement, when pavement is needed, cool pavements are a promising alternative to conventional pavements to reduce elevated nighttime air temperatures.

From these three research studies, I suggest three areas for future research on neighborhood UHIs. First, although I found evidence of the cooling effects of highly reflective pavements, because they are on the ground level much of the reflected light may simply be absorbed by adjacent walls and structures. Although I examined sky view factor, a future study should quantify and evaluate neighborhood configuration factors more thoroughly including examination of floor view and wall view factors as suggested by Erell and colleagues (2010). What is the relative contribution to elevated air temperatures of pavement to wall surfaces in dense urban canyons? Second, future research should focus on the longer impacts of in-situ cool pavement and other UHI reduction strategies so we can provide better and more detailed best practice to cities implementing UHI reduction strategies. A systematic placement of many weather stations in close proximity may better articulate how pavement impacts air temperature at finer scales over longer periods of time. The length of time will vary depending on the research question. Yet, analyzing these pavements for several months to a few years will help researchers to better understand how these pavements impact air temperature in various conditions throughout the year. Based on my studies it is likely that light winds will largely determine the strength of the relationship between the cool pavements and air temperature. Finally, future research should focus on the co-benefits of UHI strategies. UHI reduction and stormwater strategies have similar design strategies (increase permeable surfaces to infiltrate stormwater and increase local moisture) but are used for different reasons. For instance, although white roofs might provide the biggest cooling impact on reducing residential energy use, how might using a green roof in lieu of a white roof impact both heat and stormwater? The results from these types of studies will be an important contribution to UHI reduction research and planning efforts. City officials are taking action on reducing UHIs. We must provide these officials with sound and useful methods for analyzing neighborhood environments for both UHI analysis and reduction.

Appendix

Appendix A: Regression Analysis for UHI Temperatures at 2 a.m. in Eight Chicago Neighborhoods during 62 Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.08***	0.02	-0.18	-0.03	0.01	-0.06	-0.01	0.02	-0.01
% Impervious				5.63***	0.51	0.57	6.74***	1.18	0.68
% Tree Canopy				-1.18***	0.40	-0.15	-1.38***	0.48	-0.18
Urban Canyon							-1.04	0.80	-0.15
Orientation							0.26	0.16	0.11
(Constant)	1.26***	0.11		-3.23***	0.51		-3.89***	0.84	
n		496			496			496.00	
Adjusted R2			0.30***			0.49***			0.50
Change in R2			0.03			0.47			0.00

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Appendix B: Regression Analysis for UHI Temperatures at 4 p.m. in Eight Chicago Neighborhoods during 62 Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.01	0.02	-0.01	0.00	0.02	0.00	0.02	0.02	0.03
% Impervious				-1.08	0.75	-0.10	-2.41**	0.90	-0.22
% Tree Canopy				-3.67***	0.59	-0.42	-2.86	1.71	-0.33
Distance to Industry							-0.68***	0.13	-0.48
Upwind % Tree Canopy							0.02	0.02	0.21
(Constant)	1.23***	0.13		2.91***	0.74		4.16***	0.83	
n		496			496			496	
Adjusted R2			-0.002			0.12***			0.17***
Change in R2			0.00			0.12			0.06

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Appendix C: Regression Analysis for UHI Temperatures at 2 a.m. in Eight Chicago Neighborhoods during 12 Heat Event Days in Summer 2010

	Model 1			Model 2			Model 3		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.07	0.03	-0.20	-0.02	0.02	-0.07	0.01	0.03	0.04
% Impervious				4.31***	0.84	0.56	5.94***	1.91	0.78
% Tree Canopy				-1.31	0.66	-0.22	-1.90*	0.77	-0.31
Urban Canyon							-1.75	1.29	-0.33
Orientation							0.53*	0.26	0.28
(Constant)	1.04***	0.20		-2.31**	0.84		-3.22*	1.36	
n		96.00			96.00			96.00	
Adjusted R2			0.03			0.56***			0.58
Change in R2			0.04			0.54			0.02

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Appendix D: Regression Analysis for UHI Temperatures at 4 p.m. in Eight Chicago Neighborhoods during 12 Heat Event Days in Summer 2010

	Model 1			*Model 2*			*Model 3*		
Variable	B	SE	*Beta*	B	SE	*Beta*	B	SE	*Beta*
Neighborhood	-0.03	0.06	-0.06	-0.02	0.06	-0.03	-0.004	0.06	-0.01
% Impervious				-0.30	2.03	-0.02	-1.54	2.46	-0.12
% Tree Canopy				-4.54**	1.60	-0.43	-3.09	4.70	-0.29
Distance to Industry							-0.69	0.36	-0.41
Upwind % Tree Canopy							0.02	0.06	0.12
(Constant)	1.42***	0.35		2.63	2.01		3.82	2.29	
n		96			96			96	
Adjusted R2			-0.01			.15***			0.18
Change in R2			0.00			0.17			0.05

*p < .05. **p < .01. ***p < .005 (one-tailed tests).

Appendix E: Details of the Green Alley Program

Program goals were 1) to use recycled local pavement materials, 2) to balance permeability with strength of pervious pavements, 3) to lighten concretes with recycled slag, and 4) to incorporate monitoring and maintenance. First, the pavements needed to contain recycled and local materials available to contractors. By 2006, CDOT was installing pilot projects with as much as 45% recycled asphalt concrete combined with 15% recycled PCC concrete in new asphalt concrete mixes (Attarian, 2012). CDOT also used slag in the PCC mix at a rate of 100 pounds per cubic yard (Attarian, 2010). Second, they had to balance the strength of the pavement with permeability. CDOT estimated that each alley had to handle 200 passenger vehicles a day, along with at least two single-unit trucks and one multiunit truck (Attarian, 2010). CDOT decided that a compressive strength of 11,720 kPa (1,700 psi) for the pervious concrete of was acceptable. This compressive strength standard is nearly identical (11,721 kPa) to the recommended strength recommended by the FDOT (2007) study. In terms of permeability, CDOT's pavement designs included 20% voids in the pervious PCC and 25% voids in the pervious HMA. In addition, CDOT was able to substitute ground low cost recycled tire rubber for fibers that are typically added to the polymer modified asphalt cement in the pervious HMA to prevent drain-down. The rubber tires adhered to the asphalt cement better than the fibers and increased the pavements durability by increasing the surface temperature range for rutting and cracking. Permeable pavers were spaced 12 millimeter or 0.47 inch apart and filled with 0.6 cm (0.25 inch) crushed open-aggregate for drainage (Attarian, 2010).

Third, for the high albedo concrete CDOT was able to incorporate slag byproduct in the concrete and achieve an initial albedo of 0.26 (Attarian, 2012). Finally, five pilot products were monitored from 2006 to 2009 to understand changes in pavement strength, albedo, permeability, and infiltration. After the first year they found that reductions in void size, the decreased ratio of permeable to impermeable, and presence of trees reduced rates of infiltration. Based on this monitoring protocols were developed to clean permeable pavements with existing dry streetsweepers twice a year in the spring to remove debris from snow melt and the fall to remove leaf debris (Attarian, 2010). CDOT found after looking at other techniques, including vacuuming, that this protocol not only kept down costs but also restored sufficient infiltration (Attarian, 2010). They found that after sweeping pervious pavers it was necessary to refresh aggregate between pavers to ensure proper drainage.

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