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Implications of Urban Design Strategies for Urban Heat Islands: An Investigation of the UHI Effect in Downtown Austin, Texas

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Implications of Urban Design Strategies for Urban Heat Islands: An Investigation of the UHI Effect in Downtown Austin, Texas

by

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Thesis

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Dedication

This thesis is dedicated to my dad, Manouchehr, who is missed the most, and to my mom, Afsaneh, and like her namesake, the true legend of my life.

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Abstract

Implications of Urban Design Strategies for Urban Heat Islands: An Investigation of the UHI effect in Downtown Austin, Texas

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The University of Texas at Austin, 2017

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Given growing concerns about Urban Heat Islands (UHI), this master's thesis aims to document the principal factors contributing to the formation of UHIs and assess how urban design parameters can be modified to prevent or mitigate UHIs. Drawing on literature from three different areas of research (UHI causes and impacts, UHI measurement and simulation tools and techniques, and urban design strategies' influence on urban climate), the author conducted a case study of Downtown Austin, Texas, which has been rapidly growing and densifying during the past decade. To characterize the impact of the future development proposed for the downtown area in the Downtown Austin Plan (DAP), the UHI measurement tool Urban Weather Generator (UWG) was used to simulate the UHI over Downtown in 2020 and 2039 (at the end of the implementation of Downtown Austin Plan). Finally, this study proposes an urban design solution to mitigate Austin's intensifying UHI.

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Chapter 1: Introduction

In 2016, six cities in Central Texas were listed among the top 15 fastest-growing in the U.S. (U.S. Census Bureau, 2017; Richardson, 2015). That same year, Austin was named the fastest growing U.S city (Forbes, 2016). Because of the urban development and increase in Austin's population, the city is likely to experience an increase in the Urban Heat Island effect (UHI) (Richardson, 2005). A report on climate change prepared for the City of Austin projected that summer maximum temperatures will increase by 1.5-2 degree Celsius by 2040 (Hayhoe, 2014).

The U.S. Environmental Protection Agency (EPA) defines urban heat islands as "the phenomenon whereby urban regions experience warmer temperatures than their rural surroundings" (EPA, 2008). Urbanization causes natural and vegetated surfaces to be replaced by buildings, roads, and other infrastructure. This surface cover transition is known as the main contributor of UHI formation (UHIs, 2016; PA, 2008). Dark surface material, such as road pavements and roof covers, which are considered low albedo[1] material, absorb and retain the sun's radiation during the day and slowly re-radiate the heat to the surrounding environment overnight, thus elevating a city's temperature, ozone levels, energy demand for cooling, and CO2 emissions (Akbari, 2002). Moreover, extra heat in the summer can cause serious problems for human health. Different studies show a direct relationship between UHI intensity peaks and heat-related illness and fatalities (Hayhoe, 2014; Akbari, 2002; City of Austin, n.d.).

Given the significance of such an increase in UHI for public health, I propose to answer the following research questions related to UHI impacts in Austin, Texas and the role of UHI modeling more generally:

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[1] In Latin, Albedo translates to "whiteness".

1. How can simulation tools which consider design parameters help equip urban planners and designers to predict future UHIs intensity and advancing mitigation strategies?

2. How will the future development of Downtown Austin affect the magnitude of Austin's UHI effect?

3. How can Downtown Austin Plan development and design strategies be revised to also incorporate design parameters in order to potentially reduce the intensification of the UHI effect in Austin?

The U.S. Environmental Protection Agency has launched a program in order to mitigate urban heat islands. EPA's Heat Island Reduction Program (HIRP)[2] tries to translate UHI related research outcomes into outreach materials, tools, and guidance. This program is jointly sponsored by the EPA and the Department of Energy (DOE) to empower community groups, public officials, industry representatives, researchers, and other stakeholders with the information they need to develop projects to better understand UHI effects, and encourage them to create strategies and provide mitigation policies to reduce UHI impacts on energy demand, local meteorology, air quality, and health (EPA, 2017a; EPA, 2003).

HIRP consists of three main activities. First, the Urban Heat Island Pilot Project (UHIPP) was begun in 1998 with five U.S. cities as part of the Heat Island Reduction Initiative. Baton Rouge, Chicago, Houston, Sacramento, and Salt Lake City were selected based on the severity of their ground-level ozone problem, the likelihood that the city could benefit from the reduction of the UHI magnitude, availability of the data needed, and local interest in UHI mitigation programs (EPA, 2017b; Voogt, 2004).

[2] In some documents it has also been referred to as The Heat Island Reduction Initiative (HIRI).

Second, in October 2008 EPA released the Compendium of Strategies for Reducing Urban Heat Islands. The Compendium describes the causes and impacts of summer urban heat islands and promotes strategies for lowering temperatures in U.S. communities. It provides an overview of heat islands, how they form, and their impacts, and describes key urban heat island reduction strategies in depth. It also describes voluntary and policy efforts undertaken by state and local governments to mitigate urban heat islands (EPA, 2017b). In addition to these attempts, in 2008 EPA also started to hold free, national, urban heat island (UHI) webcasts. Through these webcasts, scientists, practitioners, industry representatives, government officials, stakeholders and staff from around the nation participate and discuss their work related to UHIs (EPA, 2016)

There has been great effort both in the U.S. (with the EPA) and abroad (various studies have been undertaken in different cities and climates) to understand the causes of UHI formation and to find mitigation strategies. Some well-known strategies to mitigate UHI formation include installing surface materials with high albedo (light colored or reflective material), green roofs, planting trees, and cool pavements (EPA, 2008). However, these strategies are not applicable to all cities. For example, numerous urban areas around the world face extreme weather conditions, such as drought, so strategies decreasing temperature and releasing heat through evaporative cooling, or planting trees and increasing vegetation are not practical or implementable solutions for those areas.

Another, principal contributor to UHI that is not adequately considered in such mitigation strategies is urban form and building morphology. If other strategies are not applicable for an area, modification in urban form and building masses could be key to mitigating the UHI effect. Therefore, it is necessary to evaluate urban development plans at their initial stages and consider any needed revisions. This, in turn, calls for simulation tools that can be incorporated into current design platforms, and which can encourage planners and urban designers to integrate their designs and strategies for energy and thermal comfort concepts with massing design (Nakano et al., 2015). As Ratti et al. (2003) suggest, alterations to the urban texture can be made at small scales (e.g. within the urban block) in order to improve the microclimate. However, important variables that affect microclimate and energy consumption such as urban forms, surface materials, vegetation, etc. have been disregarded (Bouyer et al., 2009). "We sometimes dispose of efficient techniques adapted to climate and to architectural culture" (ibid. P. 165).

How Visualization and Simulation Tools Can Contribute to Analyzing the Urban Heat Island Effect

Urban designs and building patterns used to respond to regional climate and environmental conditions. However, the rapid growth of cities and increased demand for housing have led to a shift away from climate sensitive design (Grimmond et al., 2010), making it increasingly important to model the impact of urban growth on UHI effect. Currently, housing, transportation, water resources, and infrastructure have received most of the attention of planners, while urban climate and the influence of the built environment on climate has received only a small share of strategic planning efforts (Coutts et al., 2010). Despite the importance of the relationship between urban form and climate, this has not been given enough consideration (Fehrenbach et al., 2001).

Weather forecasts in urban areas is necessary when developing air pollution control strategies, emergency management for situations like vast fires in dry climates, dangerous winds, intensity and frequency of thunderstorms, ozone events, and storm water management (Grimmond et al., 2010). Rapid urban development alters the ability of nature to adapt to the new condition; therefore it is important to monitor temperature change that occurs as a result of urban development. This concern has given rise to the field of urban climatology, a growing are of scientific inquiry. However, since climate knowledge is little valued in urban planning and design process (Eliasson, 2000), this is a good moment to infuse this knowledge into the planning and policy making process in order to improve our built environment.

This study demonstrates the utility of UHI modeling to inform planning and design, drawing on an analysis of UHI intensity over Downtown Austin between 2020 and 2039 (at the end of the implementation of DAP (Downtown Austin Plan). Data was gathered from the City of Austin website and also City of Austin staff, as well as different planning project coordinators involved in research of current conditions and also envisioned development. In order to simulate the UHI effect and intensity, I used Urban Weather Generator (UWG), a newly developed urban design UHI simulation tool that facilitates climate-specific analysis and allows designers to model the potential effects of proposed designs microclimate in urban areas (Nakano, 2015). UWG enables urban designers to parametrically test their building mass and density for urban scale designs and associated impacts (Nakano, 2015), and allows urban planners to recommend zoning regulations for building height, land use, transportation policies with energy and thermal implications (Nakano, 2015).

Urban Weather Generator is the first publicly available tool that incorporates microclimatic considerations in urban design and energy simulations (Nakano, 2015; Bueno et al., 2012). UWG estimates the hourly urban canopy air temperature and humidity using rural weather station data. It takes a rural epw file and the *.xml (or *.xlsm) input file, which describes the urban canyon parameters, urban morphology, geometry, and surface materials (Bueno et al., 2012; Urban Weather Generator). The model uses energy conservation principles which are used for existing building energy performance simulations (Bueno et al., 2012). Building parameters required by the UWG are the typical ones used for building energy simulations (Bueno et al., 2014).

Study Area - Downtown Austin

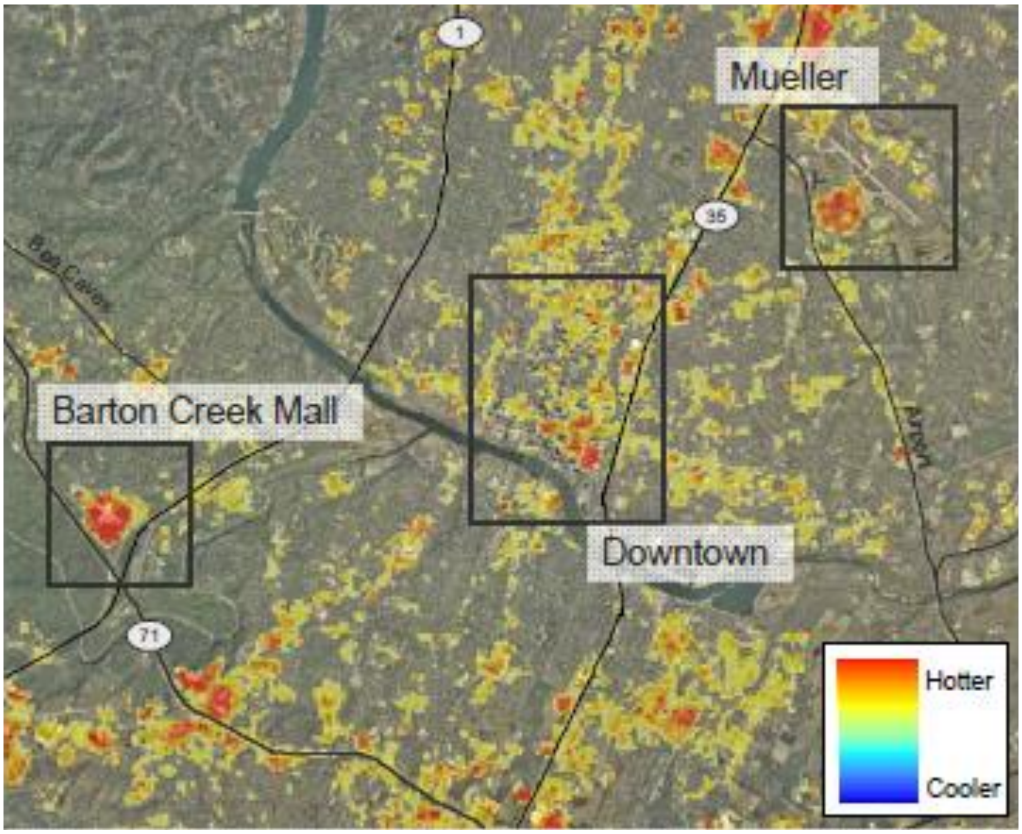
Downtown development in Austin began to rapidly increase in the early 2000s with the construction of many high-rise towers, and many more are scheduled to be built in the near future (Emerging Project Building Heights - see Appendix A). According to the Downtown Austin Plan (DAP), Downtown Austin has gone through a remarkable transformation over the last decade. Figure 1 shows how the Downtown Austin skyline changed between 1997 and 2012. The DAP, which was adopted by the Austin City Council February 2008, provides an action plan to address the challenges Downtown faces as development increases, including the loss of local businesses, lack of affordable housing, and auto-oriented streets and public spaces, and to refine the future vision for the area (DAP, 2011). The DAP aims to "assure that Downtown can evolve into a compact and dense urban district, with new buildings contributing positively to sustainability, quality of life and the Downtown experience." Therefore, both public and private sector development should contribute to make Downtown a dense, compact and sustainable place (DAP, 2011).

Figure 1. Downtown Austin Skyline in 1997 (top) and 2012 (bottom). (Johnson & Thibert, n.d.).

The DAP was based on the prediction that Downtown Austin would have 25,000 residents by 2015 (Novak, 2008). As a result, the plan calls for high-density (see Appendix B for the height limit map) development for downtown[3], which in turn would contribute to the economic vibrancy of the region and facilitate the achievement of broader goals related to diversity, affordability, quality of life, and sustainability (DAP, 2011). Even though only 12,000 rather than 25,000 people were living in the downtown area by 2015, Austin is still a fast growing city. This rapid population growth and associated developments has led to an increase in the UHI effect: a study done in 2015 reveals that between 1993 and 2011, the average surface temperature in Austin increased by 4.7 degree Celsius (Richardson, 2015), and it is likely to continue to increase (Moran, 2011).

[3] It suggests an overall 36.5 million square feet of new development in properties totaling about 149 acres in the downtown area.

Figure 2. Thermal Data Collected from a Satellite shows Downtown, Mueller, and Barton Creek Mall as the hottest Spots in Austin. (Moran, 2011)



Facing this increase in downtown temperatures, in June 2001 City Council adopted the Austin Heat Island Mitigation Resolution, making Austin one of the pioneers in the development of UHI mitigation plans. The Heat Island Mitigation Resolution required the City Manager to review recommendations for reducing and mitigating Austin's heat island. Recommendations include a range of different strategies, such as development of a cool roof program and enforcement of the city's tree-saving ordinance (EPA, n.d.). In addition, other Austin development plans and strategies contain objectives related to the heat island resolution, such as Austin's Climate Protection Plan, Imagine Austin Comprehensive Plan, and Austin Urban Forest Plan (Urban Heat Island Initiative, 2015).

As Downtown Austin grows and becomes a high-density and compact area with towers and high-rises, and considering the growing concern of the UHI effect and its negative impacts, it is important to assess the impact of proposed development on Austin's future UHI. Currently, there are no studies available or ongoing which explore these impacts. This thesis study seeks to measure UHI intensity over Downtown Austin in 2020 and 2039 using a simulation tool called Urban Weather Generator. The goal of this research is to use this tool to predict the UHI resulting from Austin's CBD future growth, and suggest design strategies to mitigate the possible intensifying effect.

In the following chapter, I describe the factors that contribute to UHI formation, and provide a review of principal impacts and mitigation strategies. In addition, I discuss the history of UHI measurement techniques and currently available tools and models. In Chapter Three I present my methods, focusing in particular on the model set-up to simulate UHI magnitude in Downtown Austin. Finally, Chapter Four provides the results of the modeling, an analysis of UHI development in Austin, and an assessment of the strengths and limitations of the modeling tool.

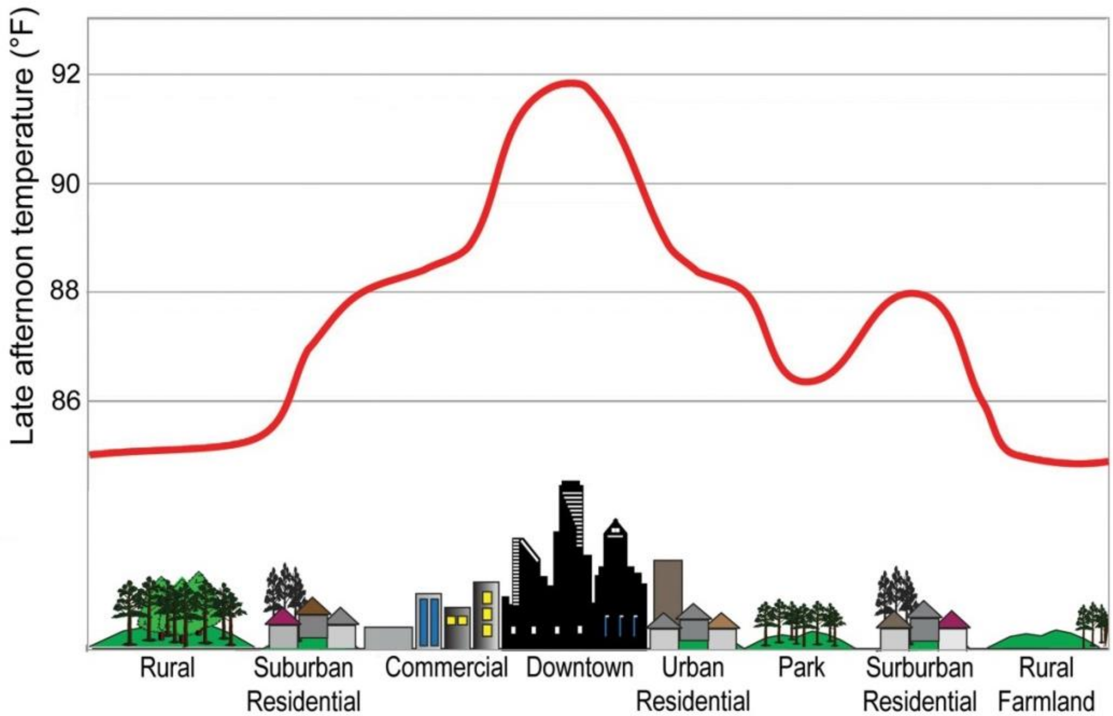
Chapter 2: Literature Review on Urban Heat Island

In this chapter, the theoretical and modeling basis for my analysis of UHI impacts in Downtown Austin is reviewed. I begin with an operational definition of the urban heat island effect, followed by discussion of (1) the physical factors that allow UHI to arise, (2) the impacts to society and natural systems from UHI phenomena, (3) the classification and measurement approaches to UHI, (4) mitigation strategies, and (5) modeling approaches to measure and evaluate UHI effects.

What is an Urban Heat Island?

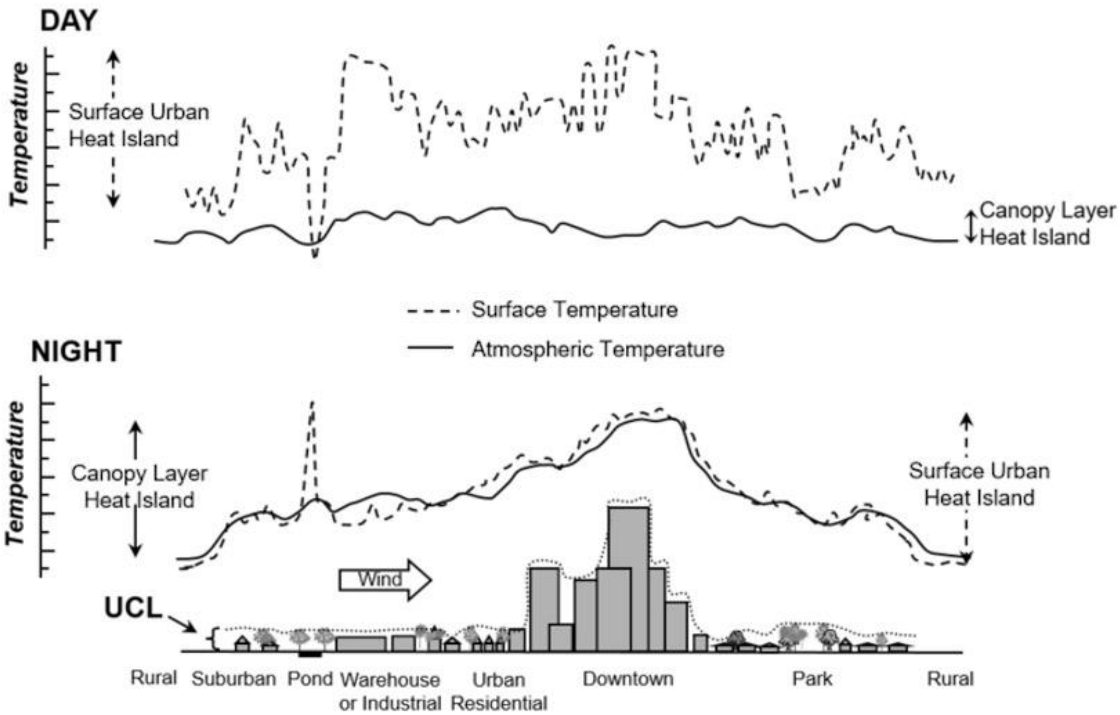
The air in an urban area is usually warmer than that in the surrounding countryside, Oke (1978) explains. This phenomenon is known as an Urban Heat Island (Figure 3). The general concept of a heat island was first mentioned or at least credited to Luke Howard, who compared the air temperature inside and outside of London using detailed temperature measurements from 1806 to 1830 (Lokoshchenko, 2014; Howard, 2012). As a phenomenon dependent on meteorological, locational and urban characteristics, the size of a heat island varies in different locations and throughout the day (Oke, 1978). UHIs are stronger at night and their magnitude increases closer to the core of urban areas, where building density is higher (Howard, 2012).

Figure 3. Urban Heat Island Profile. (Lemmen & Warren, 2004).



There are two types of heat islands: Surface Heat Islands (SHI) and Atmospheric Urban Heat Islands (AUHI) (see Figure 4). These two heat island types differ in many ways, including in how they are formed, their characteristics, and their impacts, and call for different measurement tools and techniques (EPA, 2008). Atmospheric heat islands are measured directly by thermometers, whereas the SHIs are measured by remote sensor techniques using satellites or aircraft data (Voogt, 2004).

Figure 4. The Geography of the Urban Heat Island. (Voogt, n.d.).



On summer days, temperatures of exposed surfaces, like roofs and pavements, can increase above air temperatures to between 50-90°F (27 to 50°C), while shaded surfaces remain closer to air temperatures. This surface temperature difference is known as a Surface Heat Island. SHIs remain throughout the night but are stronger during the day (18 to 27°F temperature difference during the day comparing to 9 to 18°F at night) (Climate Research Group, n.d.; EPA, 2008). On the other hand, the difference in air temperature between warm air in cities and cool air in rural areas is called an Atmospheric Urban Heat Island. Atmospheric heat islands are divided into two groups: 1) Canopy Layer urban heat islands and 2) Boundary Layer urban heat islands.

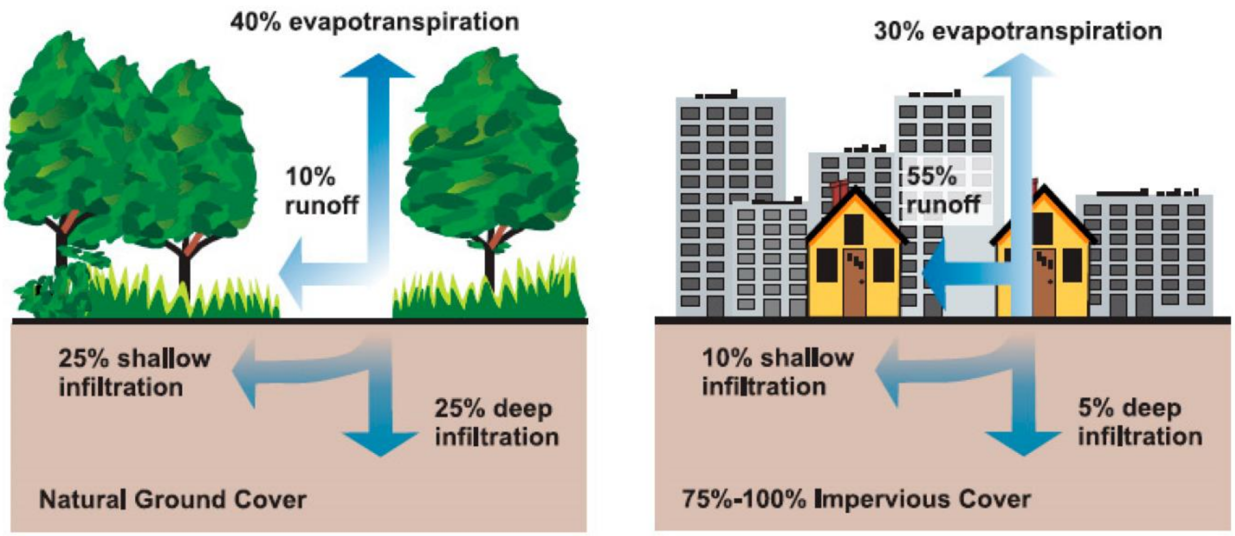
Urban Canopy Layer is the air where people live, from the ground up to the tops of trees and roofs. The Boundary Layer starts from where the canopy layer ends and extends upwards to the point where urban landscapes no longer influence the atmosphere, or not much higher than the top of the tallest buildings, and does not extend more than a mile (1.5 km) from the surface. Boundary Layer heat islands are smaller in magnitude than the other type (Climate Research Group, n.d.; EPA, 2008).

How Is an UHI Formed?

Urban heat islands are a result of urbanization, whereby the urban fabric stores the sensible heat during the day and then releases it slowly during the evening, keeping urban areas hotter than rural areas (Climate Research Group, n.d.). Sensible heat is the energy released in the atmosphere and is related to the temperature change of a gas or an object without changing its phase (Climate Education, n.d.). The main variable of the formation of heat islands is transition between land surfaces, particularly the transition from surfaces covered with vegetation to paved roads, conventional roofs, sidewalks, roads, and parking lots by development. While there are other variables that contribute to the formation of heat islands, urban surfaces have the most significant impact. Urban materials retain heat and thus block surface heat from radiating into the night sky (Richardson, 2005; Onwuchekwa, n.d.; Climate Research Group, n.d.; EPA, 2008). Studies showed that urban environments absorb twice as much heat as rural areas (EPA, 2008).

The color and composition of urban materials also contributes to the strength of the heat island effect. For example, darker materials have a lower albedo, allowing them to absorb and retain more heat than natural, vegetated and light colored surfaces (Richardson, 2005). Albedo, which ranges between 0 and 1 (0 indicating black or a perfect absorber and 1 indicating white) is a material indicator referring to the whiteness of a surface and illustrates how well a material reflects solar energy (National Snow, n.d.). Also, vegetation provides shade and provides moisture to the air, which in turn serves to cool the surrounding area. Built up areas evaporate less water, resulting in elevated surface and air temperatures (EPA, 2008).

Figure 5. Relationship between impervious cover and surface runoff. Impervious cover in a watershed results in increased surface runoff. As little as 10 percent impervious cover in a watershed can result in stream degradation (EPA, 2003).



In addition, air-conditioners and refrigeration also release a considerable amount of heat into the air, especially during summer when the energy demand is higher (Onwuchekwa, n.d.). This is heat that is vented from the operation of machinery. Industrial activities, anthropogenic heat release from building sides, traffic, and humans also contribute to the creation of higher heat islands (Climate Research Group, n.d., Onwuchekwa, n.d.). Cities with dense fabrics have a higher chance of being affected by urban heat island effect, specifically at night-, Oke (1988) argues.

What Are the Impacts?

There are a great many impacts associated with UHIs. Most of those impacts are negative while some impacts may be beneficial, such as extending the plant-growing season (EPA, 2017b), or saving energy during winter in high latitude cities (Onwuchekwa, n.d.). However, researchers and scientists are in general agreement that the negative effects greatly outweigh the beneficial impacts, especially during the summer (The Green City, n.d.). According to the United States Environmental Protection Agency, the main negative impacts of UHI include increased energy consumption, elevated emissions of air pollutants and greenhouse gases, compromised human health and comfort, and impaired water quality (EPA, 2008).

The UHI effect is significant with regards to building energy consumption. According to Doddaballapur and Bryan (2012), UHI significantly affect the energy demand for various building typologies. Since building stock represent the principal fabric of a metropolitan region, this increased energy consumption increases costs to citizens as well as governments, causing significant economic impacts. Research has found that for each 2ºF increase in temperature, there is a 2 to 4% rise in peak summer urban electric demand (Akbari, 2001). The urban heat island around Los Angeles, California, costs the city $100 million a year in energy, the Heat Island Group reports (National Geographic, 2012).

The increase in energy consumption for cooling (i.e. refrigeration and air-conditioning) creates a circle in which high energy consumption leads to an increase in energy production by power plants, thus leading to higher emissions of heat-trapping greenhouse gases (i.e., carbon dioxide) and pollutants (i.e., sulfur dioxide, carbon monoxide, and particulate matter) into the atmosphere. Furthermore, high air temperatures promoted by the UHI effect increase the formation of ground-level ozone which is a contributor to lung cancer (UHIs, 2016; EPA, 2008).

In addition to the air pollution, UHIs affect meteorological features of urban areas by reducing precipitation, snowfall, and the diurnal and seasonal ranges of freezing days. UHIs also contribute to the formation of thunderstorm events (UHIs, 2016). Moreover, high temperatures have negative influences on the physiological and phonological process of plants and urban forests (The Green City, n.d.).

Besides the well-known impacts of UHI on energy consumption, UHIs also affect residents' health by increasing heat stress during warm seasons, leading to heat exhaustion, heat syncope, and heat cramps (Grimmond et al., 2010; Onwuchekwa, n.d.; Oke, 1988; The Green City, n.d.). Heat-related illnesses occur when the body is under stress from high environmental temperatures and is not able to control its own internal temperature (Iowa State University, n.d.). For example, heat syncope happens when, due to overheating, the body does not have adequate blood flow to the brain, causing the person to lose consciousness (Korey Stringer Institute, n.d.)

Excessive heat and air temperature increases can result in above-average rates of mortality. The significant impact of heat on human health is considered "deadly weather-related phenomena," and many people die because of unexpected increases in air temperatures (Grimmond et al., 2010; Oke, 1988). According to The Centers for Disease Control and Prevention data, "from 1999 to 2010, a total of 7,415 deaths in the United States were associated with exposure to excessive natural heat" (QuickStats, 2012), which is more than the total number of mortalities due to hurricanes, lightning, tornadoes, floods, and earthquakes (Onwuchekwa, n.d.). This is not only limited to the U.S. In 2003, a heatwave killed approximately 70,000 people in Europe, including over 15,000 people in France alone (National Geographic, 2017). In 2009, the Australian provinces of Victoria and South Australia experienced a heatwave that killed 432 people (NewaComAu, 2016). Vulnerable groups, such as people already suffering from ailments, people recovering from illness, pregnant women, elderly and children are the groups most affected by heat island impacts (Urban Green, n.d.; The Green City, n.d.).

Due to the large surface area of impervious pavement in urban areas (nearly 30–45% of land cover, based on an analysis of four geographically diverse cities1), paving materials are an important element to consider in heat island mitigation (EPA, n.d.). Conventional paving materials can reach peak summer temperatures of 120–150°F (48–67°C), transferring excess heat to the air above them and heating stormwater as it runs off the pavement into local waterways.. Tests have shown that pavements that are 100ºF (38°C) can elevate initial rainwater temperature from roughly 70ºF (21ºC) to over 95ºF (35ºC). Also, the temperature of rainwater runoff from hot roofs and roads can rise from a few degrees to as much as 17°C on hot summer days

This heated stormwater drains into storm sewers and raises water temperatures as it is released into streams, rivers, ponds, and lakes. When warm water from the UHI flows into local streams, it stresses the native species that have adapted to life in a cooler aquatic environment (National Geographic, 2012). Rapid temperature changes in aquatic ecosystems resulting from warm stormwater runoff can be particularly stressful, even fatal to aquatic life (EPA, n.d.). Some species of fish, for example trout, are particularly susceptible to morbidity from spikes in temperature in their aquatic habitats (Bell, 2006). Higher surface water temperatures can also cause botulism, a type of poisoning caused by a growth in bacteria that are particularly lethal to fish and birds. Certain bacterial substances also present a danger to humans (EPA, 2008; Urban Green, n.d.).

UHIs also increase water consumption. A study conducted in Phoenix demonstrated that the elevated temperatures resulting from Phoenix's UHI contribute significantly to greater water use in single-family homes, which results in economic and long-term sustainability consequences (Guhathakurta & Gober, 2007).

How to Measure the UHI Effect

In the early days of UHI research, studies primarily focused on empirical measures of climate in different urban locations, and on the relationship between city population and UHI magnitude. Later, researchers, using physical models of cities, studied and observed the physical processes of the heat island effect. Studying physical models helped to understand this phenomenon qualitatively (Street, 2013). A disadvantage of this method is that physical models are the most common tools to study energetic fluxes in order to understand urban processes, yet the urban energy fluxes is too complex for physical models to provide a clear and easy understanding of this criterion. However, despite this fact, scaled aerodynamic models of urban areas are still being used in multiple fields (CITATION).

Although urban climatology has not been given enough attention, there has been noticeable progress in scientific understanding in relation to climate measurement and modeling tools, and a greater attention to sustainable cities (Grimmond et al., 2010). According to Oke (Grimmond et al., 2010; Street, 2013), horizontal atmospheric conditions are categorized into four scales:

1. micro-scale (street), 10-2 to 103 m
2. local-scale (neighborhood), 102 to 5 x 104 m
3. meso-scale (City), 104 to 2 x 105 m
4. macro-scale 105to 108 m

At a small scale (i.e. larger than the micro-scale and smaller than the meso-scale), a person experiences a range of conditions from areas exposed to sunlight to windy corridors or shaded areas in a park or under trees (Grimmond et al., 2010). At this scale, there are certain features that need to be considered: "(a) surface roughness length, because it influences wind flow; (b) impervious surface fraction, as it is key to energy partitioning between heat and moisture exchanges; (c) sky view factor as it influences solar access and radiative cooling; (d) thermal admittance as it modulates heating and cooling cycles of materials; (e) albedo as it influences surface heat absorption and (f) anthropogenic heat flux as it is an additional source of energy for the system" (Grimmond et al. 2010: P. 248).

Different Tools

Grimmond et al. (2010) categorizes prediction and modeling tools in four groups:

1) Scale models (e.g. wind tunnels).

These require different laboratory facilities and measurement tools, are not cost efficient, and have limited applicability for full-scale studies (Grimmond et al., 2010). The computational fluid dynamics (CFD) method is an example of a scale model that can be used to accurately predict the heat island effect in a particular area. However, the high computational cost of these models limits both the size (few urban blocks) and the period the simulation is running for. Therefore, these models are not considered useful for annual calculations or a city-wide study (Bueno et al., 2014).

2) Statistical models

These models provide estimates of how cities influence urban climates. They have low computational requirements, do not need many user inputs, provide accurate results, and are relatively simple to calculate. Although statistical models have low computational requirements, the lack of a physical base is considered a disadvantage for many of these models. Also, some of the statistical models are location oriented and can only be applied to the city they were developed for, need data from a long observation period, and require different references (Grimmond et al., 2010).

3) Numerical models

Numerical models are widely covered by CFD models. These models can be used to calculate airflow at micro-scales based on particular assumptions. In order to assure that accurate results are generated, “the CFD models require input of a good meteorological profile on the upwind edge of their geographic domain and a need to adjust model parameters,” Grimmond et al. (2010: P. 256) argue. Due to the computer memory and speed efficiency these models need, having a clear and detailed canopy layer flow is still challenging (Grimmond et al., 2010).

4) Dispersion and air quality models

These models range from very simple single equation models to very complex CFD models. Equation models parameterize the urban boundary layer and its controls on dispersion, while complex models calculate with high precision and resolution driven using computer speed and storage capacity. Dispersion models distribute to predict and estimates short-term emergency response to long-term health effects (Grimmond et al., 2010).

Despite the fact that all these different models exist, currently urban planners and even energy consultants rarely use modeling tools and methods to study the UHI effects of their urban designs (Nakano et al., 2015), and such modeling tools are “delayed” in the architecture field (Aikona 2015). According to a study by Samuelson et al. (2012) of simulation and modelling tools in architecture, 37% of participants replied that energy simulations “rarely” or “occasionally” affected the design decisions. Although statistical and numerical modelling are available to predict the UHI effect (Grimmond et al., 2010), they either require a high computational cost or have a limited spatial and time related scope (Bueno et al., 2014). While some attempts have been made to simulate microclimatic conditions in urban planning and design, these simulation tools and techniques, such as ENVI-MET (Nakano et al., 2015), require a different graphic user interface than the 3D mass modeling currently used by designers and architects.

Oke (1988) suggests that urban climatology is a predictive science, and therefore findings from such research can be misleading for planning and design professions. This makes it difficult to know whether “urban climate research has quantitative guidelines to offer regarding street geometry” in order to help make “choices between alternatives.” This is particularly true as there is a wide area of future climate scenarios due to various climatic context, urban fabrics and different designs goals. However, although it is impossible to predict climate with certainty, it is still possible to develop general guidelines for climate modeling which are flexible enough to account for different variables.

Recently, various studies have been carried out to evaluate, analyze and simulate UHI in different cities and areas around the word, including different climates ranging from dry to tropical weather within the continental USA (Zhang et al., 2010), and in Taiwan (Lin et al., 2008); London, England (Kolokotroni et al., 2006); Manaus, Brazil (Souzaet al., 2012); Singapore (Roth & Winston, 2012); and Shanghai, China (Tan et al., 2010). Observing and predicting urban climate changes at different spatial scales will foster knowledge development among those are involved in planning and decision making process, so they can contribute to developing new mitigation strategies and adopting urban growth to local climate factors (Grimmond et al., 2010).

Most of these studies have been based on site observation and data collection. However, this research method is of limited utility if planners and urban designers want to consider climate-UHI effects or other climate-sensitive consideration in their strategic planning and policy making. Currently, we lack tools which can simulate the impact of future developments in a city on urban climate. This limitation is particularly important for dense downtown areas, where most construction happen, where high-rises are concentrated, and typically where UHI effects are most pronounced).

Today, simulation and visualization tools are central to the development in many different scientific fields. "It was claimed that visualizations are practiced as a reliable and valid substitute for the real world in its different situations for the future predictions," Appleyard (1977: P.49) argues. A reliable simulation is described as one which produces a cognitive, affective, and behavioral response similar to the response given to a real world situation (Bergen et al., 1995). Despite all of the efforts made to include as many aspects of the real environment as possible in visualizations, it has been accepted that an error-free, flawless illustration of the complicated real world is neither possible nor worthwhile in terms of cost and time (Ervin & Hasbrouck, 2001). The main virtue of visualization is to enhance the communication of information and provide a better decision making process (Sheppard, 2005). Visualization in urban planning processes or large-scale simulations in planning have not received as much attention as in architecture. For instance, no reliable and cost efficient is broadly available tool to simulate the energy exchange, wind flow, and other microclimate factors for a neighborhood or larger scale. Part of this problem is due to variation between climates and how different they act in different regions or even within different urban blocks in a city. Most tools have limited and small databases available to run the simulations, or they are climate specific. Planning is a long-term process, and therefore many criteria and factors must be considered when making predictions. Therefore, development of cost efficient and user-friendly models and techniques for planners and urban designers significantly contributes to the involvement of urban climatology in planning and design processes.

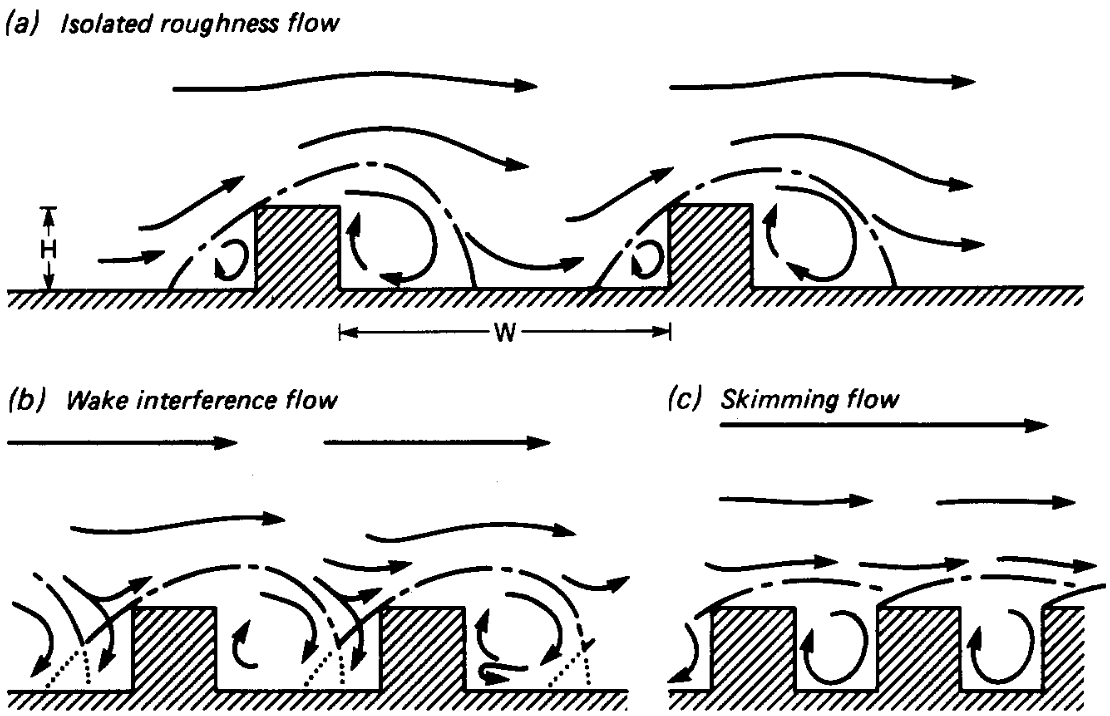
Urban Design Approaches to Mitigation

Urban design has an immense impact on urban climate, which in turn affects residents' sense of comfort in open spaces (Oke, 1978). The urban streets are defined by three factors, constituting different geometrics: 1) height/width ratio; 2) sky view factor (SVF); and 3) orientation along its long axis (solar orientation). Depending on the various geometries of streets, open spaces also display a large pallet of forms and surface characteristics (Oke, 1978). A city's climate is influenced by several parameters mostly specific to the sites under investigation. Urban geometry, vegetation, water level, anthropogenic factor, and surface properties are the main variables forming the microclimate of an area (Oke, 1978). Microclimates are also affected by local meteorological conditions, the climatic zone, and seasonal variations. The complexity of the relationship between each of these factors makes it difficult to quantify the impact of individual parameters using empirical methods (Oke, 1978; Niachou, 2008; Santamouris, 1999).

Streets and pathways usually cover more than 25% of the area of a city and therefore, the form of street canyons has a significant influence on urban climate. Simulations on E–W and N–S oriented streets indicated considerable diurnal air temperature differences in the urban canopy layer (UCL) (Oke, 1981). Different studies

(Oke, 1978; Ratti et al., 2003) show that urban geometry and built form notably affect the microclimatic behavior of the urban canopy layer (UCL). For instance, street canyon geometry and orientation have an influence on both the indoor and outdoor environment, the solar gain of interior spaces and building facades, and the urban wind velocity, which in turn provides natural ventilation for cooling urban areas (Shishegar, 2013). Each of these parameters has a direct relationship with UHI intensity. For example, a study conducted in Athens (Priyadarsini & Wong, 2005) showed that airflow is the main contributor in decreasing the air temperatures in urban canyons. Urban winds also depend on the overall density of the urban area and the number of high-rise buildings, and can also be modified by changing design elements such as the size and height of individual buildings, and the orientation and width of the streets (Priyadarsini & Wong, 2005) (see Figure 6).

Figure 6. Wind flow in urban canyons with different geometries (Oke, 1988).



Not only is there a relationship between those factors mentioned before and UCL, but there are also interactions between those factors. Shashua et al. (2006) conducted a study to see how urban geometry affects the cooling capacity of trees. The results show a significant negative relationship, meaning that the effect of a given area of trees is reduced by deepening the open space.

Oke (1988) in his article about Urban Canyons, limits the geometric factor to two measures:

1) Aspect ratio: Ratio of the average height of the canyon walls (H) to the canyon width (W): H/W[4]

[4] Oke considers H/W 0.5 as a wall apart of the buildings where the flow fields do not interact.

2) Building density: ratio of the plan or roof area of the average building to the lot/unit ground area occupied by each building (~ = Ar/A1).

In this context, mainly two factors are taken into account: the street's axis azimuth and the solar azimuth. Empirical studies and simulation research (Setälä et al., 2013; Elnahas & Williamson, 1997; Rosenfeld et al., 1995) were conducted for the two most common and extreme cases: N-S and E-W oriented streets. The results show that the distribution of the diurnal solar radiation varies between these two cases. On average, the N–S orientation permits more light penetration into the street with low values of the aspect ratio (H/W <0.5). Oke and Nakamura (1988) suggest an aspect ratio ranging between 0.4 - 0.6 for mid-latitude cities, which represents an acceptable number in meeting thermal criteria, and is favored by a large ratio, and pollution criteria, which is best fulfilled by a small ratio. Later, in his study on cities with different latitudes, Arnfield (1990) argued that this range is also applicable to all other latitudes, in regions with a high frequency of heavy cloud cover, and where street geometries do not have a considerable impact on the solar access (Shashua-Bar et al., 2004). In addition to the street geometry, the form of the buildings on the edge of the street affects the microclimate of urban open spaces.

The variation in thermal behavior of the urban streets may be related to the effect of geometry, which creates a certain lack of symmetry in relation to solar exposure of the urban canyon during the day. Climate, air temperature, and precipitation in urban areas, has been predicted to have negative influences on human health (McMichael et al., 2006; Patz et al., 2005).

Another key variable in UCL microclimate is vegetation, more specifically shade trees. Research (Shashua-Bar et al., 2004; Dimoudi & Nikolopoulou, 2003) showed that only the evaporative cooling effect of trees in parks and streets, not considering the shade they provide, can reduce summer mid-day air temperatures for about 3 to 4degree Celsius. The cooling effect of trees not only affects their immediate surroundings, but also extends beyond the site. Shashua-Bar & Hoffman(2000) found that a small tree planted in an area can cool down its surroundings up to 100 meters from the site boundary, while in large green areas, such as parks and green open spaces, the cooling effect was perceivable up to 2 km from the site (Jauregui, 1990). Recent studies show the importance of passive cooling in modeling the relevant control elements, which can be reached through the use of ‘‘cold’’ materials (Doulos et al., 2004) and evapotranspiration from plants and watering (Lee et al., 2014). This is the reason scientists and planners are greatly interested in using vegetation evapotranspiration and tree shading as UHI mitigation strategies (Bowler, 2010; Alberti, 2009).

In addition, vegetation is different from urban materials in aerodynamic properties, thermal properties, and the ability to moisturize their surroundings; therefore, they decrease air temperature through a different process than cool materials (Sani, 1990; Taha, 1997; Givoni, 1991). However, it should be considered that the cooling and evaporation effect can critically depend on the type of vegetation. For instance, tree cover may trap warm air beneath the canopy; in contrast, an open grass field that does not block the air flow may elevate cooling by convection (Chang et al., 2007; Bona, 1997). Trees and vegetation absorb water through their roots and emit it through their leaves—this movement of water is called “transpiration.” A large oak tree, for example, can transpire 40,000 gallons of water per year (EPA, 2008). However, as it was mentioned before, not all cities and urban areas, specifically those that are located in dry regions or are facing drought, are able to benefit from vegetation and tree planting to mitigate UHI. Generally, if design mitigation strategies, like improving thermal effects of the building geometry and widespread use of cool surfaces and vegetation are combined together in cities, it significantly cools down urban areas and reduces energy consumed for cooling purposes notably throughout a year. Simulations showed a savings of about 20% over the course of a year (Rosenfeld et al., 1995).

Today, the UHI effect is one of the most concerning phenomena resulting from rapid urban development. This air temperature difference between urban core and surrounding rural areas has significant and negative consequences on urban residents' health, energy consumption, water and air quality, and economic condition of people and government. All of these impacts are connected to each other, so if one factor increases, the others do so as well. The need to foresee the impact of urbanization on urban climate, measuring UHIs, and evaluating mitigation strategies is indisputable. There are some tools and techniques currently available to measure heat islands, but most of them have time, scale, and scope limitations, and are not cost efficient, therefore, many urban planners, designers and even energy consultants do not have access to these models. Thus, the need for a cost effective, time efficient, readily accessible and user-friendly built environment model is growing. If such a model becomes accessible, proposed strategies will be evaluated in the early stages of the planning and design process, and design variables, like building masses, height, open spaces, etc. can be revised, since vegetation and tree planting are not applicable UHI mitigation strategies in many places.

Chapter 3: Austin's UHI Policies and Study Context

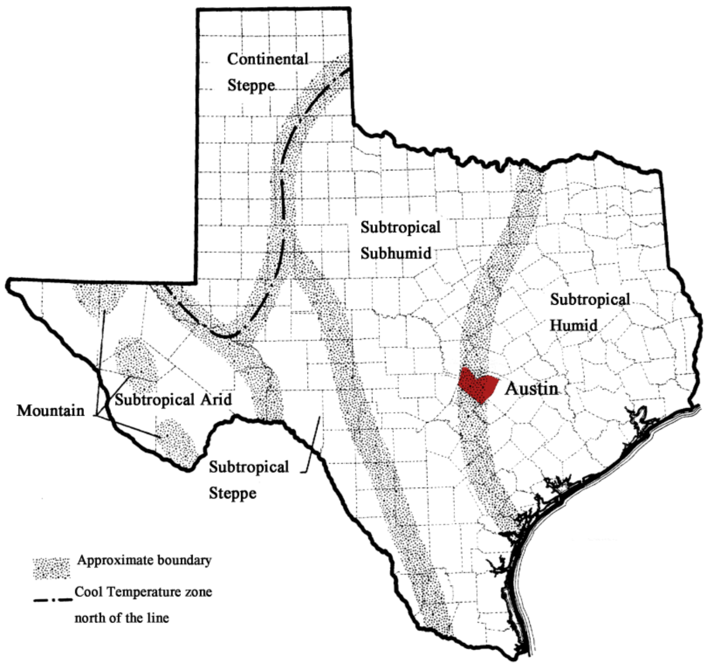
Austin

This chapter introduces the case study location—Austin, TX—to apply the UHI modeling and justifies the selection of the downtown district for modeling purposes. The chapter describes the Austin climatic context and the city policy efforts to date to reduce UHI impacts. Notable from this analysis is the fact that the city is aware of and concerned about UHI impacts and is taking important steps to reduce UHI. However, to date the city has not had district scale models to inform such efforts.

Austin (the capital of Texas) is located in Central Texas. According to the U.S. Census data, Austin, with a population of 947,890, is ranked 11th of the top 15 most populated cities in the US and was among the fastest growing cities in 2016 (Ward, n.d.). With more people rapidly moving to Austin, construction development sites can be seen all around the city, from downtown to the city borders.

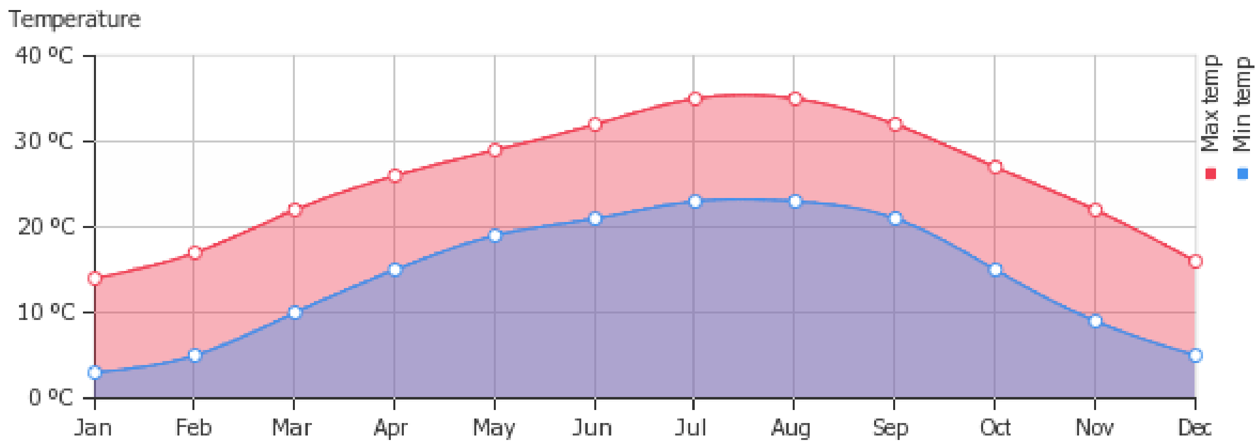
Generally, Texas is famous for having warm weather. Austin is located on the border of two different climate zones, a sub-tropical humid climate and a sub-tropical sub-humid climate (see Figure 7). Both of these climates zones have warm summers, and the sub-tropical sub-humid climate has dry winters. Austin experiences both extremely humid and less humid weather throughout the year as a result of lying between these two climate zones (Ward, n.d.).

Figure 7. Region of Climate Classification in Texas. (Climatic Atlas of Texas, 1983)



The average monthly temperatures vary 40 degrees between the lowest and highest months; i.e. January and August, respectively. It needs to be noted that if the level of humidity is high, it affects the human temperature with higher extremes in the summer and cooler extremes in the winter (Ward, n.d.). Austin has a moderate annual level of precipitation and the average values range from 32 to 36 inches per year.

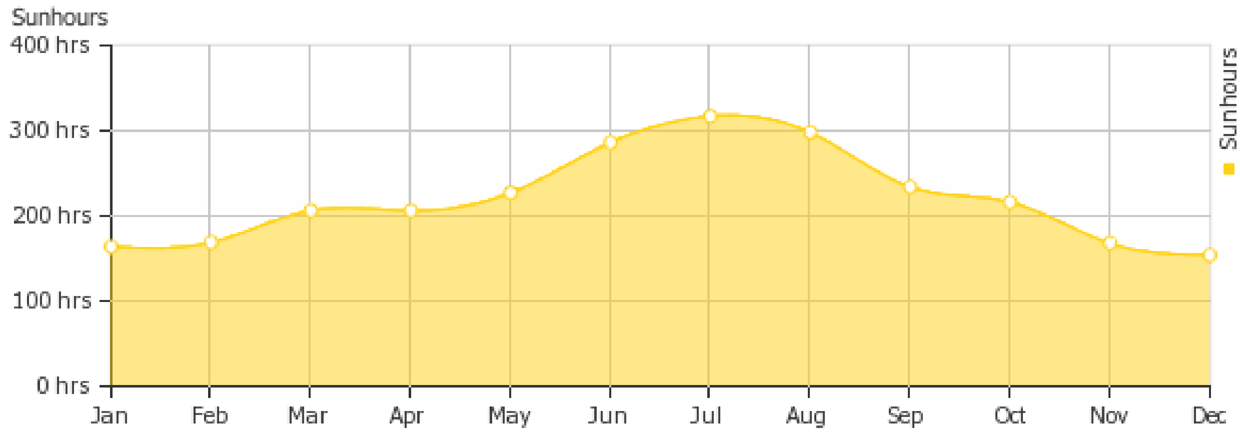
Figure 8. The Monthly Mean Minimum and Maximum Temperatures Over the Year in Austin. (Weather and Climate, n.d.)



Austin is located at a low latitude of 30°N and therefore receives a large amount of sunlight. During the summer, Austin usually gets 15 hours of daylight; in the winter daylight is reduced to 11 hours. Because Austin typically does not have a dense cloud cover, it has a high availability of sunlight ranging from 50–75% throughout the year. Figure 9 illustrates the monthly total of sun hours over the year in Austin. This considerably impacts the heat island effect due to the extreme solar heat buildings and materials gain and absorb (Ward, n.d.).

The dominant wind in Austin blows from the North and South Axis, with some variety to the East. In general, the average wind velocity is under 24 m/h, with the majority of the winds ranging from 8 m/h to 11.4 m/h (Ward, n.d.).

Figure 9. The Monthly Total of Sun Hours Over the Year in Austin. (Weather and Climate, n.d.)



UHI in Austin and the City's Approach

In January of 2001, a heat island seminar was conducted by City Council members with participation from community leaders and experts from the public, private, and non-profit sectors. Following the seminar, a working group was formed to develop a comprehensive set of recommendations to mitigate the heat island effect in Austin. The recommendations were later established as the Heat Island Containment Policy, which was passed by City Council in June of 2001. The main goal behind this effort was to reduce energy consumption during peak summer hours, and decrease air pollution and storm water runoff which are the most well-known consequences of urban heat islands. See the Heat Island Working Group recommendations in Table 1.

Table 1. Heat Island Working Group Recommendations. (Urban Heat Island Initiative, 2015)

No.	Recommendation
1	Adopt light-colored roof strategies
2	Expand program for green commercial properties
3	Adopt light-colored pavement strategies
4	Increase funding for commercial energy management program
5	Incentivize/enforce city tree-saving ordinance
6	Adopt ordinance for mandating 50% canopy coverage within 15 years for all new parking lots
7	Adopt landscape ordinance requiring 30% shade cover within 5 years for all hardscape
8	Improve/enforce the 1% requirement for trees in CIP roadway ordinance
9	Adopt bus stops tree shade policy
10	Change billing method for tree planting donations
11	Expand city tree planting programs
12	Provide tree mapping and inventory project
13	Protect urban forest as part of city infrastructure
14	Adopt landscape easement policy

The primary efforts of the Heat Island Working Group were mostly concentrated on reflective roofs and increasing shade tree plantings. Since then, the city has been trying to practice and implement these recommendations through a variety of code requirements, focused initiatives, and subsequent plans (Urban Heat Island Initiative, 2015). Currently, reflective roofs are a code requirement for all new commercial roofs, there is new emphasis is on tree planting programs[5], and there is outreach to the public as

[5] According to Keep Austin Green (n.d.), each year, approximately 6,000 trees are being planted as part of the city's Heat Island program.

well as educational efforts (Urban Heat Island Initiative, 2015). In addition, Austin began the Climate Protection Plan in 2007 when Texas was identified as the most polluted state in the U.S. (Muraya, 2012). In a webcast conducted by the EPA in August 2012, Norman Muraya from Austin Energy discussed Urban Heat Island mitigation activities taking place in Austin, as well as heat island prevention strategies and technologies, with an emphasis on cool roofs. He mentioned that Austin's fast growth rate, with the population doubling every 20 years, has concerned residents in the city with regards to the heat island effect.

Currently, Austin's Climate Protection Plan incorporates UHI initiatives through green building and energy efficiency programs and plans, including the Energy Efficiency Services, the Urban Heat Island Initiative, the Austin Climate Protection Plan, and the Austin Green Building Program. As part of UHI initiative, the City of Austin introduced six ways that Austin residents can help in reducing the urban heat island effect:

1. Cool Roof[6]

The City of Austin follows the EPA's definition of a cool roof: "Cool roofing products are made of highly reflective materials that can remain approximately 50° to 60°F cooler than traditional materials during peak summer weather" (City of Austin, 2012a; EPA, 2008). Materials used in cool roofs have high albedo and light colors to reflect a higher percentage of sunlight and gain less solar energy, thus reducing heat gain and indoor temperature, and reducing energy consumption and costs up to 40% (City of Austin, 2012a). Cool roofs lower ceiling surface temperature about 4.7°F (2.6°C) (Cool California, n.d.; EPA, 2008).

[6] "Cool roof" refers to the use of highly reflective and emissive materials.

2. Green Roof[7]

Green roofs mitigate the heat island effect in various ways. Their function is similar to that of other vegetated areas, such as reducing solar gain and heat absorption, as well as reducing the re-radiation that occurs during evening (keeping the exposed area hotter for longer). Green roofs cool down the roof area by evapotranspiration which results in a 4°–11ºF cooler surface than the surrounding ambient air (Taha, 1997; City of Austin Green Roof Advisory Group, 2010). By comparison, dark or black roofs are 55° to 85°F hotter than the ambient temperature (EPA, 2008). Green roofs provide more urban heat island mitigation than other roof types (City of Austin Green Roof Advisory Group, 2010). Based on the City of Austin Green Roof Inventory, there are currently only 10 buildings located in the downtown area (within the boundaries of the case study of this research) which have green roofs[8] (City of Austin, n.d.) (see Appendix C).

3. Green Wall

Green walls, also known as living walls, work like vertical gardens that attach to buildings. They are especially useful for sites which do not have enough room to plant trees or plant traditional gardens (City of Austin, 2012b). Plants in living walls absorb the hot air and create cool and lower density air around the building envelopes through photosynthesis and evapotranspiration. Based on thermodynamic laws, the air heated by pavements and buildings moves toward the cooler areas with lower density and cools down when it reaches green areas like living walls, reducing UHI effects by lowering air temperature and improving air quality (Maslauskas, 2015). Moreover, because of the lower air temperature, green walls reduce energy use for cooling devices by up to 20% in

[7] According to EPA (2008), "Green roof" refers to rooftop gardens.

[8] According to the City of Austin, projects that incorporate green roofs can earn incentives from the City of Austin.

summer, as well as insulate building envelopes in winter, thereby lowering the energy demand for heating buildings (City of Austin, 2012b). In addition, they have beneficial value to residents' health and well-being by reducing the amount of toxins in the air, improving the habitants' concentration levels, and enhancing their productivity (Maslauskas, 2015).

4. Cool Pavement[9]

There is not an official definition or standard for cool pavement. According to the EPA, cool pavement "mainly refers to reflective pavements that help lower surface temperatures and reduce the amount of heat absorbed into the pavement" (EPA, 2008). The City of Austin considers cool pavements mainly as materials and construction techniques that are used to lower the amount of solar absorption and heat gain (City of Austin, 2012C). Basically, cool pavements reduce the surface temperature by allowing air, water, and water vapor into the voids in the pavement, which keeps the pavement moist. Air flow and evaporation then keep the pavement surface cooler on hot days (EPA, 2008). According to EPA (2008), cool pavement technologies have not been enhanced as much as other heat island mitigation strategies. For instance, there is no official standard or labeling program to define cool paving materials."

In most U.S. cities, pavements cover 35–50% of surface area (Heat Island Group, n.d.; Chao, 2012). Pavement coverage is about 30–45% of land cover in Austin (City of Austin, 2012c). About half of that paved area includes streets and pathways and about 40% are uncovered exposed parking lots, mostly constructed using dark materials (Chao,

[9] In Los Angeles, the annual building conditioning (cooling + heating) PED and energy cost savings intensities yielded by cool pavements were each about an order of magnitude smaller than the corresponding savings from cool roofs.

2012), with surface temperatures reaching up to 120–150°F (48–67°C) on summer days (City of Austin, 2012c; EPA, 2008).

Newly paved street asphalt absorbs 95% of the sunlight that reaches it, and newly constructed cement concrete pavement absorbs about 65% of sunlight (Heat Island Group, n.d; Cool California, n.d.; Tran, 2009). However, as time passes, the reflection factors of both of these materials change. For street asphalt, sunlight absorption decreases to about 75% after seven years of use due to oxidation and wear from vehicle traffic. In contrast, cement concrete gets darker in color over a period of five years, so the solar absorption increases to approximately 75% (Cool California, n.d.; Tran, 2009).

Cool pavement reduces storm-water runoff by absorbing the runoff into the pavement. This absorption also acts to filter pollutants, therefore improving water quality. Additionally, because cool pavements are more reflective and have lighter material color, they enhance visibility at night, saving energy by requiring fewer lighting devices. Another benefit of cool pavements can be found in parking lots or other areas where people gather or children play; when covered with cool pavements, these areas provide a more comfortable environment since the surface temperature is lower (Heat Island Group, n.d; EPA, 2016).

5. Trees

As previously mentioned, green and vegetated areas significantly reduce the air temperature and UHI effect, making it the mitigation strategy most favored by planners and urban designers. Trees and other leafy plants reduce their surrounding air temperature through transpiration by absorbing water from the soil and releasing the vapor through their leaves (City of Austin, 2012d). Moreover, they absorb 70 percent of the sun's energy, keeping the area below them cooler (EPA, 2008).

Using trees as a mitigation strategy is useful when they are planted in the right location (i.e. not blocking desired sunlight during wintertime). Factors like tree species, rate of growth and size at maturity, and whether they are deciduous or evergreen are also important when planning for an urban area. For example, faster growing species will provide shade more quickly, but may have shorter life spans (City of Austin, 2012d; EPA, 2008). For Austin, a native and drought-tolerant tree species that is adapted to hot and sub-humid climate should be selected, considering a hotter climate and increased drought is expected to come in the decades ahead (City of Austin, 2012d).

6. Shading

Installing shading structures and adding shade to outdoor areas is a reasonable immediate substitute for vegetation shadings since slow-growing trees can take decades to mature. Casting shade on an outdoor area reduces the air temperature by reducing the amount of sunlight reaching the urban surface, as well as reducing energy used for cooling devices. In addition, shading provides protection from sunburn, skin cancer, and heat-related illness, as well as improving the thermal comfort of outdoor spaces (City of Austin, 2012e).

Planting trees or building shade structures are helpful strategies to be considered as UHI mitigations, but they are not deep and long term solutions for negative impacts of UHIs. For example, trees might be destroyed or removed due to storms and strong winds. Moreover, it usually takes years, compared to the rapid development of urban areas, for a tree to become mature and contribute to reducing air temperatures. Although Austin has long been trying to mitigate the heat island effect, this work has mostly revolved around tree and green plantings as well as individual effort, and less around policy making, neighborhood and building design regulations (like considering H/W ratio), or requiring open space between high-rises. The city has never applied a micro-scale UHI simulation model to inform its UHI strategies. The following two chapters describe the model used in this thesis and the results as a means to both explore the utility of the GW model for policy as well as make clear its usefulness for design intervention.

Chapter 4: UWG Methods, Assumptions and Modeling

Urban Weather Generator

This thesis uses the Urban Weather Generator (UWG) to explore the utility of UHI modeling to inform plans and design guidelines, using Austin, TX downtown district as a test bed. The reasons I selected this model for my analysis are as follows:

(1) Publicly accessible and free. The simulated results are comparable to more computationally expensive mesoscale atmospheric models.

(2) The model does not require a graphic user interface to run the simulation. In other words, it works stand-alone without requiring a digital 3D modeling tool plug-in.

(3) The model works for different weather stations and for all weathers. Previous studies that used UWG to simulate UHI have been conducted in different climate zones such as mild climates (Toulouse and Basel), tropical climates (Punggol, Singapore) and cold climates (Boston Financial District, MA).

(4) Time efficiency; each set of simulations takes a few minutes to an hour to run.

The UWG model is a bottom-up building stock model[10] that uses energy conservation principals to estimate "the UHI effect in the urban canopy layer using meteorological information measured at an operational weather station located in an open area outside the city, accounting for the reciprocal interactions between building and the urban climate" (Bueno et al., 2012; Bueno et al., 2014). UWG can estimate building energy consumption both at the city and at district scale. The model is capable of

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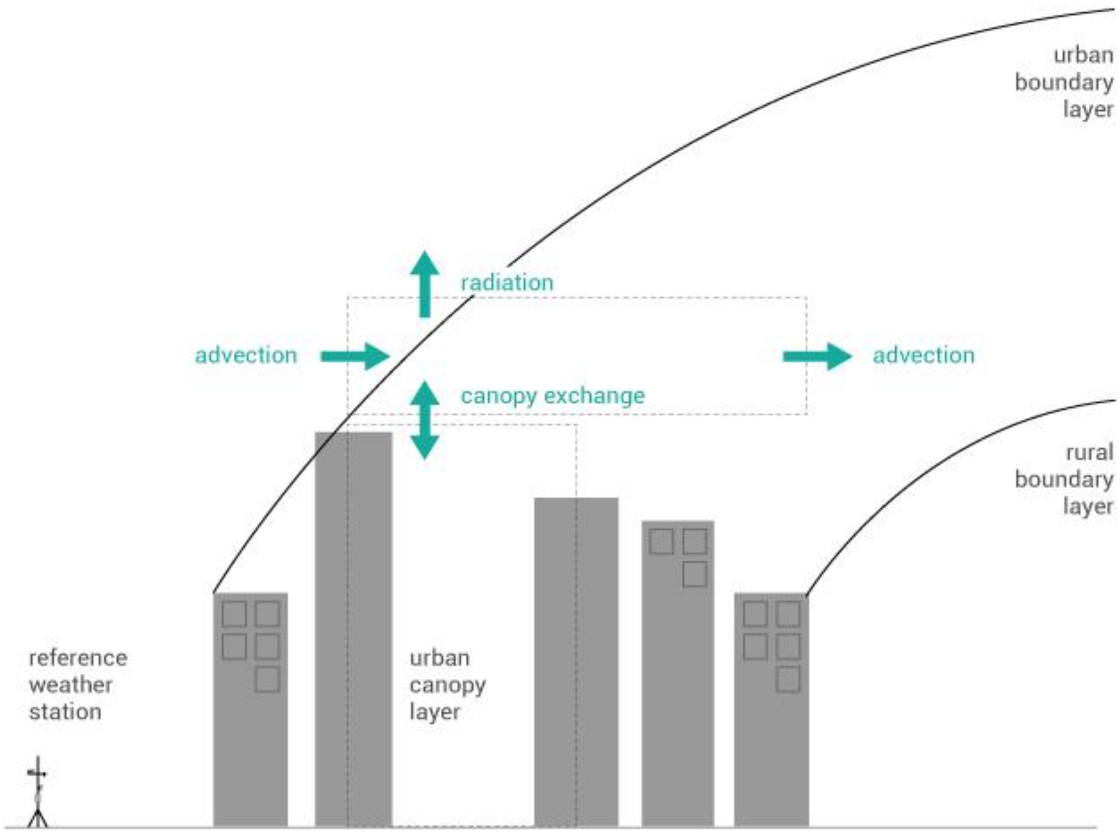
[10] Building stock models are tools to assist with the efficient implementation of building energy consumption policy, and estimate the baseline energy demand for existing building stock.

considering different neighborhood characteristics and various building uses within the study area, while taking into account the longwave radiation effects of water vapor and CO2 in the urban boundary layer. UWG also considers the surface roughness on the airflow and the tree canopy area (Nakano, 2015; Bueno et al. 2014). UWG is one of the few examples of "an environmental model of the urban climate scaled to the same order of computation as building thermal simulation" (Street, 2013). UWG is computationally efficient and takes into account the interactions between buildings and urban climate (Nakano, 2015).

UWG Modules and Function

According to Bueno et al. (2012), UWG calculates urban air temperature and humidity on an hourly base using weather data measured at an operational weather station located on a rural area. UWG simulates UHI based on neighborhood-scale energy balances (Nakano, 2015).

Figure 10. The boundary conditions of the urban canopy and urban boundary layers are shown here. The model estimates building energy consumption at the city scale, specifically accounting for the interactions between buildings and the urban environment. (Urban Weather Generator, n.d.).



UWG is composed of four coupled modules:

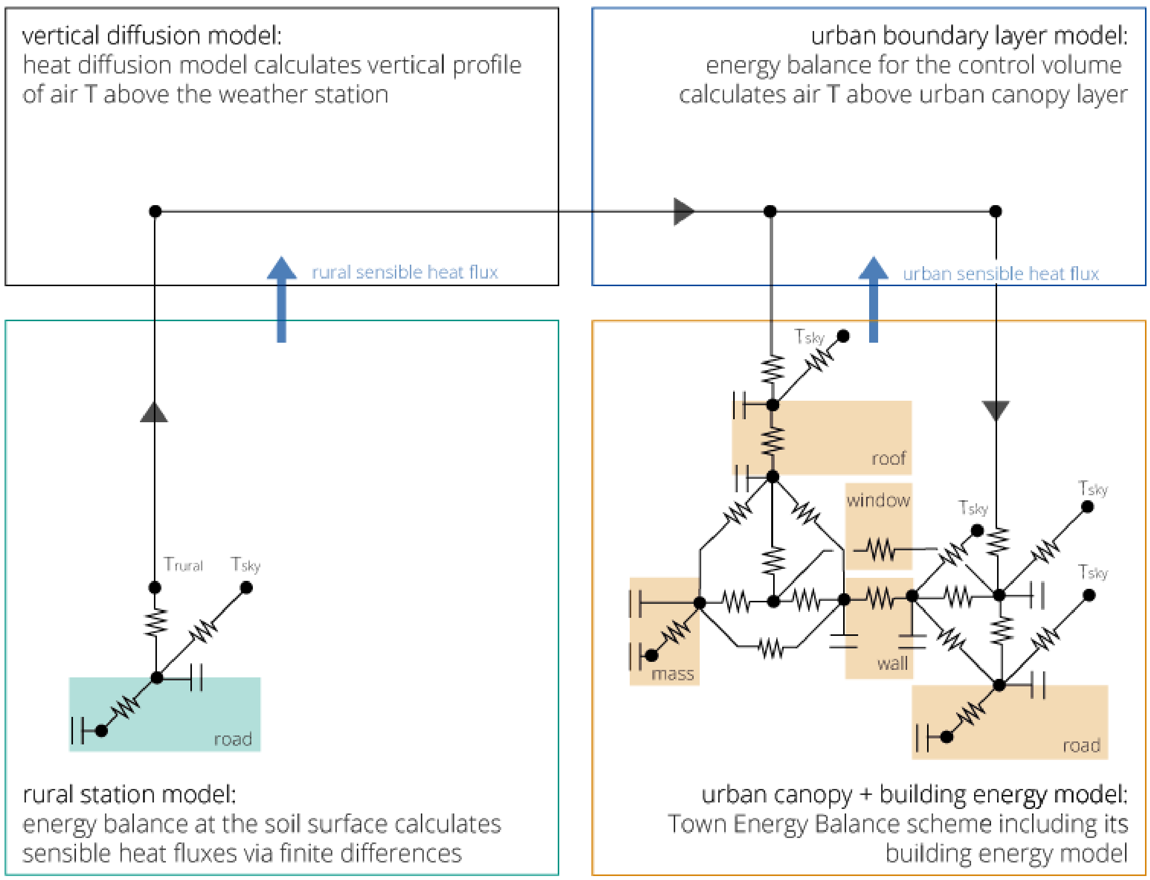
1) Rural Station Model (RSM), which calculates sensible heat fluxes at the weather station;

2) Vertical Diffusion Model (VDM), which calculates vertical profiles of air temperature above the rural site;

3) Urban Boundary-Layer (UBL) model, which calculates air temperatures above the urban canopy layer (above urban canyons);

4) Urban Canopy and Building Energy Model (UC-BEM), which calculates urban sensible heat fluxes and urban canyon air temperature and humidity.

Figure 11. UWG Modules Interaction. (Urban Weather Generator, n.d.).



UWG was initially used to generate weather data for Basel, Switzerland, and Toulouse, France, and the results were evaluated against the available data collected on Basel (Rotach et al. in 2005) and Toulouse (Masson et al). Comparing the results of each study with the field data illustrated that the UWG error, which was about 1K, lies between the air temperature variability, exists in different sites of the same urban area, and was considered acceptable and comparable to a more computationally expensive mesoscale atmospheric model (1.7K) (Bueno et al., 2012; Street et al., 2013; Nakano, 2015). Later, temperature measurements were carried out in Singapore (Bueno et al., 2014) and Boston (Street et al., 2013) to evaluate the model in climate zones different than the European cities. The UWG model error stayed within the same range as the previous study, and UWG was therefore considered to be able to generate temperatures for different climate zones and be applied to different configurations to calculate the UHI.

UWG basically uses a combination of energy balance calculations with building energy models used in EnergyPlus algorithms. In UWG, the study area is defined by three parameters:

- Average building height,
- Horizontal building density,
- Vertical-to-horizontal urban area ratio (VH).

Instead of using a complex definition for the structure of the study area, these parameters draw it into a "homogenous depiction" as defined by the Town Energy Balance (TEB) scheme (Masson, 2000). The TEB scheme applies numerical methods to an atmospheric model (Street, 2013). TEB model is a "physically based" urban canopy model that demonstrates the thermodynamics and fluid dynamics impacts of an urban area on the atmosphere (Bueno et. al., 2011a). TEB models see urban canopy as a two-dimensional approximation formed by three generic surfaces: a wall, a road, and a roof (Bueno et al., 2011b). Initially, the TEB model was introduced to enhance the illustration of urban surfaces in meso-scale climate models (Street, 2013). To run the model, the user needs to input four variables: geometric and local parameters, radiative parameters, thermal parameters, and building model parameters (Street et al., 2013), all which are typically publicly available data.

The limitation to UWG is that the model is not able to calculate "very site-specific" impacts on the microclimate due to its simplicity (Bueno et al., 2014). This means that the model is not capable of specifically showing which building is intensifying the heat island effect and should be revised in order to improve the thermal condition of the neighborhood (Nakano, 2015). However, Bueno et al. (2014: P. 3) adds that "the model is still robust enough to produce plausible values across urban morphology and vegetation parameters based on model validation in three different sites." Since the software considers microclimate parameters, urban characteristics and vegetation parameters as well as building types, it enables both planners and urban designers to advocate for zoning regulations (i.e. building height and land use) and parametrically test building densities for master plans (Nakano, 2015).

Justification of Case Study Location

This thesis follows the Downtown Plan to define the study area as the 1,000 acres located between Martin Luther King Boulevard., IH 35, Lady Bird Lake and Lamar Boulevard (see Figure 12). This area has undergone a fast and remarkable transformation. The skyline has drastically changed over the past decade, and the area is now home to many high rises and condo towers. According to the U.S. Census Bureau, about 4,000 people were living in the Austin Central Business District in 2000. In the early 2000s, downtown development started to take place, especially the construction of many mid-rise condo projects up to twelve stories high (Novak, 2015). In 2005, the City projected to have 25,000 residents living in the downtown area in 2015. By 2015, the population had not reach that number but, according to the Downtown Alliance, the downtown area had increased to 12,000[11] people (Novak, 2015; Rockwell, 2015). All of these developments have transformed Downtown from an employment center to a neighborhood with a live, work, and play environment.

The Downtown Austin Plan (2011) includes various visions for the Austin CBD. One of the visions that is the most relevant to this study is to have "A dense[12] and livable pattern of development" which encourages the construction of high-rise and tall towers. This kind of development supports a vibrant day- and night-time environment. The density promotes economic vibrancy which in turn supports other DAP objectives such as diversity, affordability, quality of life, historic preservation and sustainability. However, the "tall and slender towers" mentioned in the DAP are one of the main causes of the formation of the heat island in Downtown Austin.

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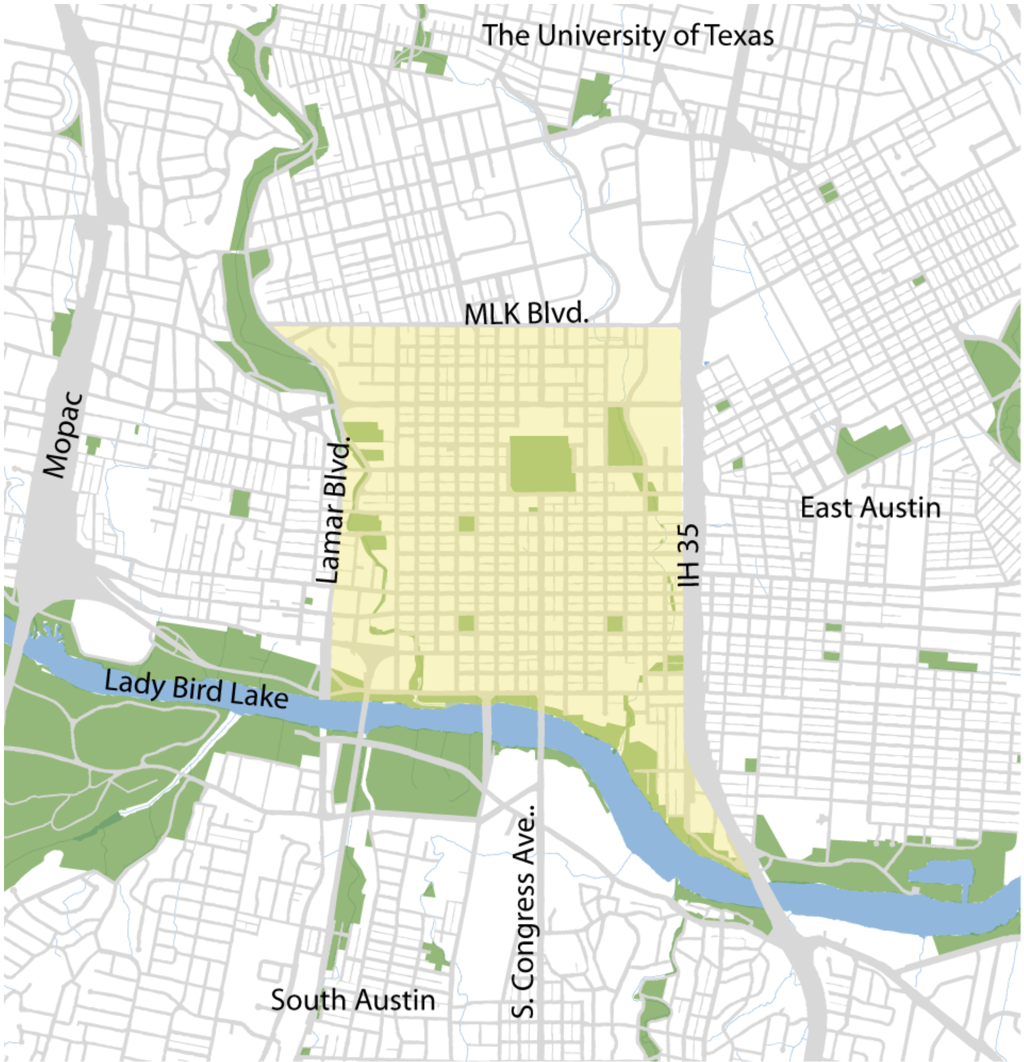
[11] A report written by the city's Economic Development office staff mentions the area bounded by Lady Bird Lake, Lamar Boulevard, Interstate 35 and 11th Street as where most of the downtown population is concentrated, a number totaling 11,700 people.

[12] DAP suggests an impervious cover of ¾ acres for the downtown area compared with 26 to 32 acres for suburban projects, and properties should have a Floor Area Ratio (FAR) of 8:1 in the Central Business District (CBD).

Figure 12. Downtown Austin Area. (DAP, 2011).



Sensitivity Analysis

Urban Weather Generator requires more than fifty user inputs to run a single simulation. These inputs include many variables, such as day and night boundary layers, for some of which there is no data or information available. The sensitivity analysis helps to identify variables which have the most impact on the UHI intensity, speeds up and facilitates simulation running processes, and requires a shorter amount of time to complete a single run by increasing the number of inputs needed. Moreover, "it helps the user to estimate the inputs that are not readily accessible (i.e. meteorological parameters) can be approximated by existing measurements," (Nakano et al., 2015). This helps the user employ default values for the parameters that are not site-specific or do not significantly impact UHI magnitude (Nakano, 2015; Bueno et al., 2012).

For the Austin UHI sensitivity analysis, one parameter was changed at a time and the model was run. The results were evaluated against the initial simulation result to identify the parameters with the most impact on Austin's UHI. The initial model was run using Austin weather data[13] in .epw format, obtained from EnergyPlus weather data inventory.

Results showed that as in all the previous studies, coverage ratio and façade-to-site ratio are the most sensitive parameters for UHI. However, unlike in other case studies, such as Boston (Nakano, 2015), the sensitivity analysis for downtown Austin shows that urban vegetation does not significantly impact the UHI intensity, although the effect of vegetation on road surface is considerable.

Model Setup

This study aims to model Austin UHI effect resulting from the downtown developments. To illustrate the impact of downtown future development on the UIH magnitude, two sets of configurations were run for two different periods of Downtown Austin development: 1) the current UHI (considering all the development currently under

[13] UWG did not run when a TMY3 file was used for Austin, therefore it was replaced by a TMY2 file: "The TMY2 are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories, because they represent typical rather than extreme conditions."

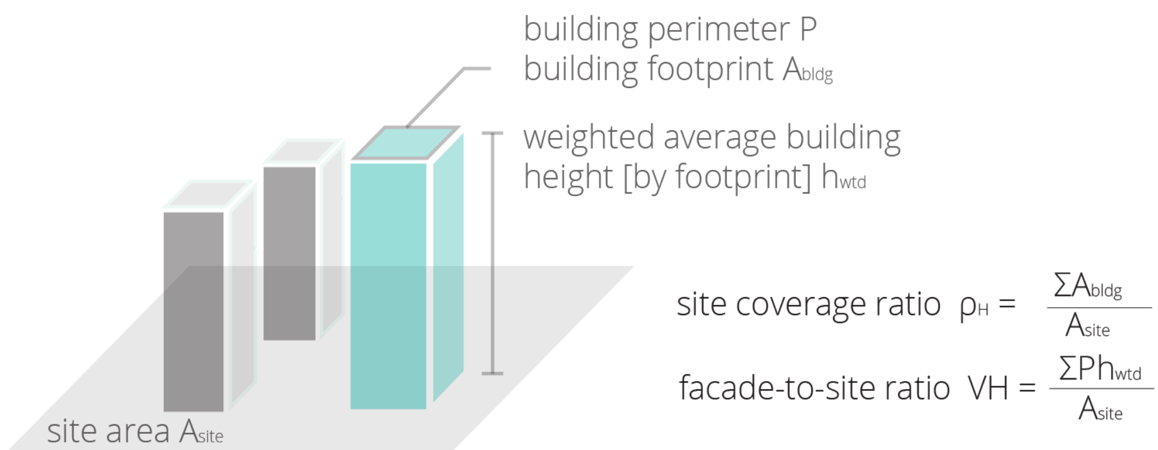
construction will be completed until 2020); 2) Downtown development plan construction, for which a vision is set for 2039. In addition, each model configuration was set up to both the warmest (August) and coldest (January) months of the year (see Figure 9). Other parameters were extracted from Geographic Information Systems (GIS) data and satellite images.

There was no data available for some of the parameters required in the model input. According to the sensitivity analysis, as well as previous study using UWG, they are not very significant in changing the UHI effect. Therefore, the recommended values listed in the UWG website (Urban Weather Generator, n.d.) were used in this study's model configurations. If a parameter has a minor impact on UHI magnitude and seems to not be significant in studies conducted in different climates, then it can be assigned a "default value" (Nakano et al., 2015; Nakano, 2015). The definition and recommended values are listed in Appendix D.

Downtown Austin in 2020

To set the model to measure the current HUI in the downtown area, urban morphology data was gathered using the latest version of GIS (V. 10.5, ESRI, 2016). Building area, height and perimeter were extracted from the GIS file, building_footprints_2013.shp obtained from City of Austin GIS Data portal (City of Austin GIS/Map Downloads). The data obtained from the City of Austin website represented building area and height in 2013, so it was updated with footprints of buildings constructed after 2013 as well as the new constructions that are going to be built until 2020. Building heights were updated using the list of "Emerging Project Building Heights" (see Appendix A). Building areas were adjusted using Google Maps aerial images for 2017 captured from Google Earth Pro. The inputs for urban geometry parameters (which define urban canyon shape) were calculated as shown below:

Figure 13. Urban geometry parameters calculation. (Urban Weather Generator, n.d.).



The meteorological parameters describe the derived urban boundary layer. The daytime and nighttime urban boundary layer heights are obtained from previous mesoscale atmospheric simulations, through experimentation, and through observations. There are no observations or previous studies done in Austin, therefore the recommended values were used for the configuration (Urban Weather Generator, n.d.).

According to Stewart and Oke's Urban Classifications (2012) (see Appendix E), Downtown Austin (in 2020) is a combination of two groups: the "open high-rise[14]" class and "compact low-rise[15]" class, which Stewart and Oke (2012) describe as "compact low-

[14] Stewart and Oke (2012) define this Urban Class as open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). And concrete, steel, stone, and glass construction materials.
[15] According to Stewart and Oke (2012) this Urban Class is dense mix of low-rise buildings (1–3 stories), few or no trees, Land cover mostly paved, and stone, brick, tile, and concrete construction materials.

rise with open high-rise." Based on these urban classifications as well as Sailor's (2011), the sensible and latent anthropogenic heat is usually about 10-20 and 1-2, respectively[16], for these urban classes. Since these parameters are not very significant in changing the UHI effect, the recommended values were used in the model[17] (Urban Weather Generator, n.d.).

Urban vegetation coverage area was estimated from satellite images and also GIS data (parks.shp) retrieved from City of Austin GIS and map inventory. Urban tree coverage area was calculated using Tree Canopy 2014.shp retrieved from City of Austin inventory and adjusted with current satellite image from Google Earth Pro. Rural road vegetation coverage was also estimated from satellite images.

Parameters used in configuration one (Downtown Austin in 2020) are summarized in Table 2;

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[16] The exact values are hard to obtain for these parameters, therefore default values were used to run the model.

[17] The author contacted the lab and it was suggested to use these values.

Table 2. Configuration one (Downtown Austin in 2020) input parameters.

Parameter	Setting	Unit
Location	Austin	-
Latitude	30° 19' 15" N	-
Longitude	97° 45' 36" W	-
Temperature Measurement Height	3	m
Wind Measurement Height	7.5	m
Simulation Period	August 1st- 31st 2020 January 1st- 31st 2020	-
Urban Boundary Layer Height - Day	700	m
Urban Boundary Layer Height - Night	80	m
Minimum Wind Velocity	1	m/s
Average Building Height	14.923665304248	m
Building Density	0.263956653	--
Vertical to Horizontal Ratio	0.841679192	-
Urban Area Characteristic Length	2011	m
Road Albedo	0.1	-
Pavement Thickness	0.5	m
Sensible Anthropogenic Heat (Peak)	20	W/m^2
Latent Anthropogenic Heat (Peak)	2	W/m^2
Urban Area Veg Coverage	0.12	-
Urban Area Tree Coverage	0.14	-
Vegetation Albedo	0.25	-
Rural Road Vegetation Coverage	0.75	-

Downtown Austin in 2039 (at the end of implementation of the Downtown Development Plan)

In this configuration, a model was run for both the months of August and January. Building area, heights, and perimeters were updated using the Downtown Austin Plan (DAP, 2011) and the Sketchup 3D model obtained from a City of Austin staff (see Figure 14). As downtown grows, its urban classification will change. In 2039, Downtown Austin will be classified as a "compact high-rise[18] " according to Stewart and Oke (2012); therefore, sensible anthropogenic heat is estimated to be approximately 60 W/m2 based on Sailor's study (Sailor, 2011).

Figure 14. Downtown Austin Existing and Potential Build-Out of Opportunity Sites. (DAP,

[18] Stewart and Oke (2012) define this Urban Class as dense mix of tall buildings to tens of stories with a few or no trees, land cover mostly paved, and concrete, steel, stone, and glass construction materials.

Urban vegetation coverage area, urban tree coverage area, and rural road vegetation coverage were estimated from satellite images. Tree coverage was updated according to the Downtown Great Street Master Plan (2001) and data obtained from the Street Scape Planting and Accessories map (Appendix F) and the Great Street Master Plan Implementation (Appendix G), received from the program coordinator. The green area coverage was gathered from the "Austin's Downtown Parks and Open Space Master Plan" (2010) in which 150 acres of new parks and green spaces are suggested.

Parameters used in configuration two (Downtown in 2039) are summarized in Table 3;

Table 3. Configuration Two (Downtown Austin in 2039) Input Parameters.

Parameter	Setting	Unit
Location	Austin	-
Latitude	30° 19' 15" N	-
Longitude	97° 45' 36" W	-
Temperature Measurement Height	3	m
Wind Measurement Height	7.5	m
Simulation Period	August 1^{st}- 31^{st} 2039 January 1^{st}- 31^{st} 2039	-
Urban Boundary Layer Height - Day	700	m
Urban Boundary Layer Height - Night	80	m
Minimum Wind Velocity	1	m/s
Average Building Height	31.01079448	m
Building Density	0.412956604	--
Vertical to Horizontal Ratio	1.472749357	-
Urban Area Characteristic Length	2011	m
Road Albedo	0.1	-
Pavement Thickness	0.5	m
Sensible Anthropogenic Heat (Peak)	60	W/m^2
Latent Anthropogenic Heat (Peak)	2	W/m^2
Urban Area Veg Coverage	0.27	-
Urban Area Tree Coverage	0.2	-
Vegetation Albedo	0.25	-
Rural Road Vegetation Coverage	0.75	-

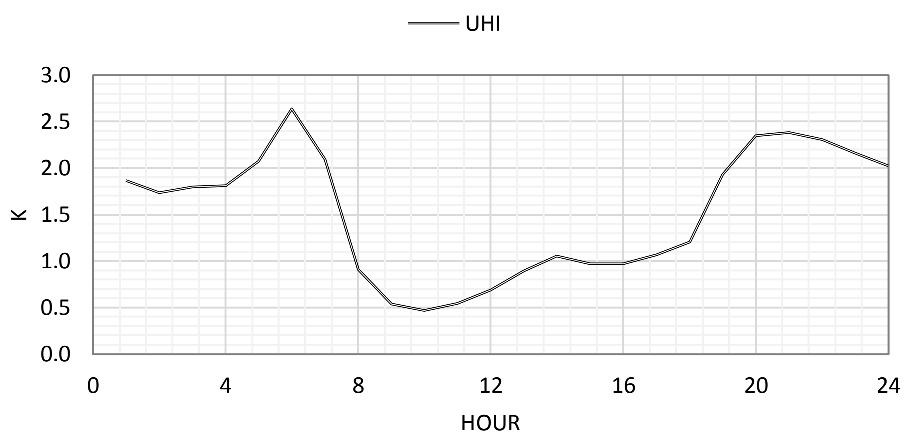
Study Limitations

Simulating UHI in Austin using the Urban Weather Generator model required various input parameters to run the model for both year 2020 and 2039. Some of the model inputs were not available for either of the configuration settings, therefore default and recommended values from the UWG developer were used instead, which reduces the accuracy of the results. In addition, for all the studies done using UWG, there was another previous study available which represented UHI effects measured using a different technique for the same case study. Therefore, it let the user compare the data retrieved from UWG with the results from the other study, thus enabling the user to evaluate UWG's accuracy. But, there was not such study previously done for Austin.

Chapter 5: Results and Analysis

Two sets of simulation were run for each configuration. Figure 15 shows how the average UHI intensity varies during 24 hours of the simulated month of August 2020. The maximum temperature difference, (about 2.7 K), between Downtown Austin and rural air temperature occurs around 6 am each day. Weather history data[19] indicates that on average, Austin experiences the lowest temperature on a daily basis around 6 am, thus the air temperature difference between rural areas (where the weather station is usually located) and the urban core reaches its maximum point in the month of August.

Figure15. Average Urban Heat Island Intensity. Configuration 1 - August. (Generated by UWG).

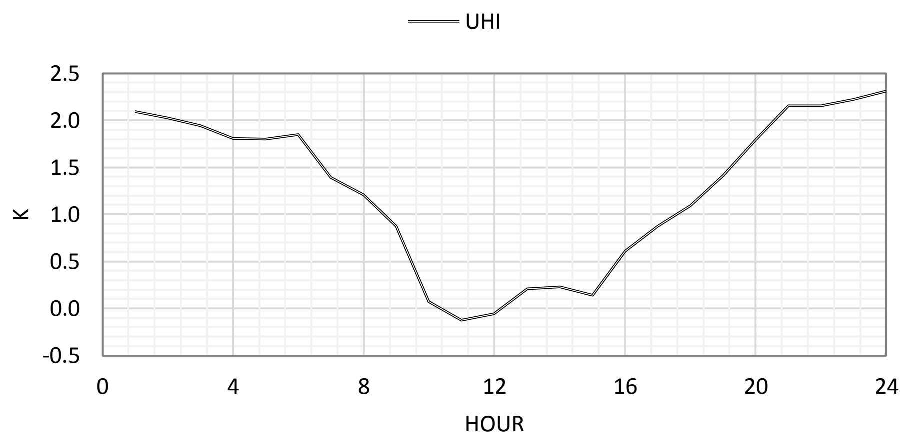


This trend changes during the month of January (see Figure 16) when the maximum temperature difference is seen around midnight, at which time the building masses in the downtown area are still releasing the heat they gained during the day,

[19] The author compared the daily weather data from 2010- 2016 for the month of August and on average, air temperature was the lowest at about 5–6 am (see Appendix H).

keeping the area warmer (about 2.2 K) than the rural areas. This results in energy saving on heating devices around the Austin's CBD, compared to rural areas.

Figure 16. Average Urban Heat Island Intensity - Configuration 1 - January. (Generated by UWG).



The UHI magnitude varies from -2° K (urban cool island) to 5° K during the course of August, and the air temperature difference between downtown and rural areas is less significant during mid-August. Unlike in the month of August, UHI is more consistent in January of 2020. The peaks seen in Figure 18 can relate to dramatic temperature ranges occurring in Austin. This significant temperature difference is not seen in summer because of the high percentage of the humidity which keeps the air warm overnight (Austin Temperatures, n.d.). But in the winter months when the air is less moist[20], air temperature can drop significantly at night. Therefore, the air temperature difference between urban and rural area (UHI) is more intense during those days.

[20] This is a result of Austin Subtropical Subhumid Climate which is known as having hot, humid summers and cool, dry winters (see Chapter 3).

Figure 17. Variations in Urban Heat Island Effect- Configuration 1 - August. (Generated by UWG).

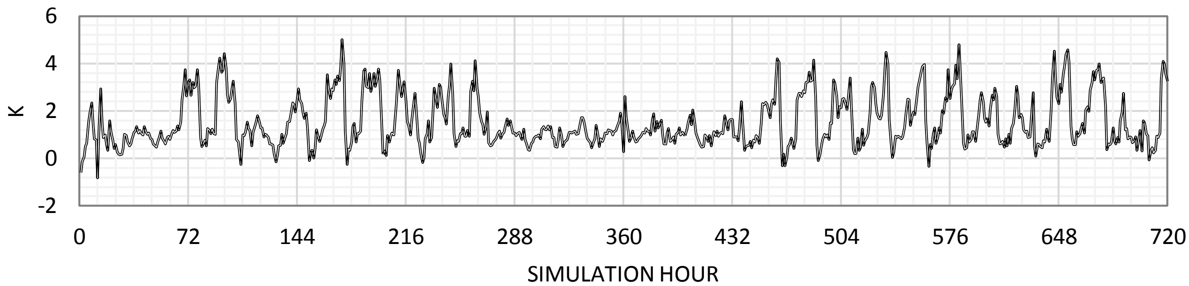


Figure 18. Variations in Urban Heat Island Effect - Configuration 1 - January. (Generated by UWG).

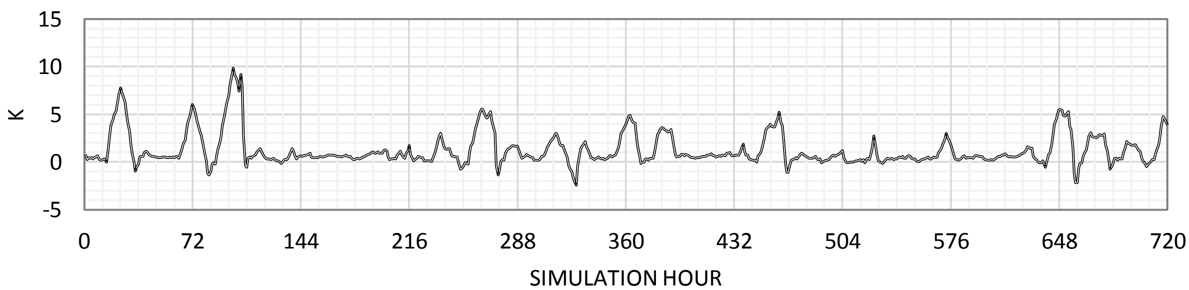
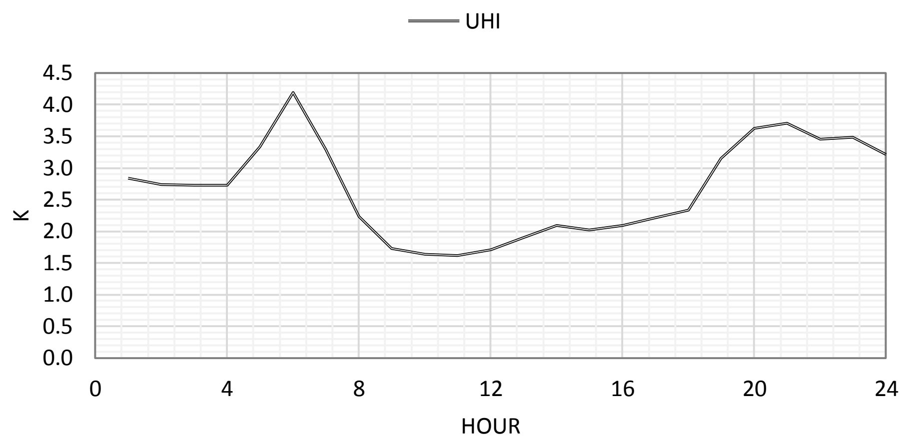


Figure 19 illustrates average UH intensity in August 2039. In August 2030, air temperature difference between the downtown area and rural Austin will be about 4.3 K, which shows an increase of about 1.6° K compared to August 2020, due to the proposed development and new constructions.

Figure 19. Average Urban Heat Island Intensity - Configuration 2 - August. (Generated by UWG).



Average UHI intensity in January will also increase by 1° K in 2039. However, like January 2020, the maximum difference between urban and rural air temperature difference is seen around midnight. Therefore, the new urban fabric does not change the trend of how UHI magnitude changes throughout the day, while it increases and changes the overall intensity.

Figure 20. Average Urban Heat Island Intensity- Configuration 2- January. (Generated by UWG).

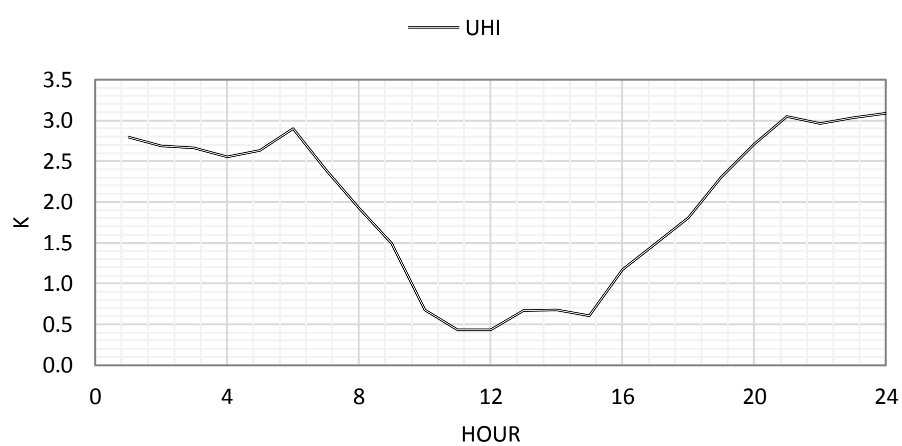


Figure 21 and 22 illustrate UHI variation for August and January 2039, respectively. Comparing these figures with the ones from 2020, an increase in UHI magnitude is seen by 2° K for the month of August in 2039, while in January 2039, the UHI magnitude is slightly different from January 2020.

Figure 21. Variations in Urban Heat Island Effect - Configuration 2 - August. (Generated by UWG).

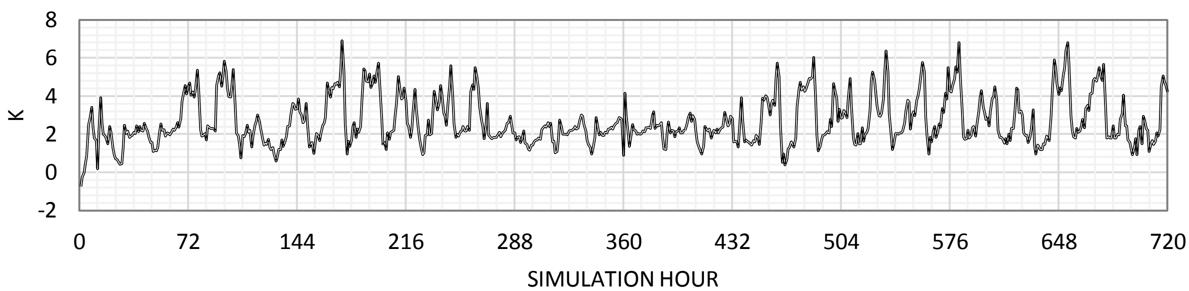
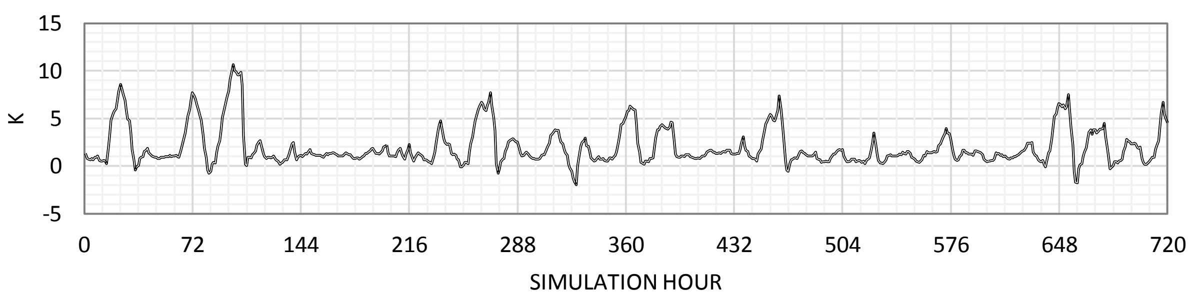


Figure 22. Variations in Urban Heat Island Effect - Configuration 2 - January. (Generated by UWG).



Comparison of these figures indicates that downtown future development will intensify UHI effects, much more so during summer than winter, and will also result in more energy demand for cooling devices over Austin's hot season. It should be noted that comparing diagrams from 2020 and 2039 only illustrates UHI variation and does not represent the actual air temperature in those years. Therefore, both urban and rural air temperature might be higher in 2039 (i.e. due to global warming) which elevates energy demand during peak summer.

In order to study the influence of design variables modification (i.e. building mass) on UHI magnitude in Downtown Austin, a third configuration was run for both months of August and January 2039. For this set of simulations, the assumption was to replace 1/8 of urban fabric with open space (no vegetated area was added or replaced). Parameters used in configuration three are summarized in Table 4:

Table 4. Configuration Three (Author Proposed Scenario) Input Parameters.

Parameter	Setting	Unit
Location	Austin	-
Latitude	30° 19' 15" N	-
Longitude	97° 45' 36" W	-
Temperature Measurement Height	3	m
Wind Measurement Height	7.5	m
Simulation Period	August 1st- 31st 2039 January 1st- 31st 2039	-
Urban Boundary Layer Height - Day	700	m
Urban Boundary Layer Height - Night	80	m
Minimum Wind Velocity	1	m/s
Average Building Height	31.01079448	m
Building Density	0.361337029	--
Vertical to Horizontal Ratio	1.325474422	-
Urban Area Characteristic Length	2011	m
Road Albedo	0.1	-
Pavement Thickness	0.5	m
Sensible Anthropogenic Heat (Peak)	60	W/m^2
Latent Anthropogenic Heat (Peak)	2	W/m^2
Urban Area Veg Coverage	0.27	-
Urban Area Tree Coverage	0.2	-
Vegetation Albedo	0.25	-
Rural Road Vegetation Coverage	0.75	-

Figure 23 and Figure 24, respectively show the average UHI intensity in August and January 2039 for the proposed scenario. Comparison between the average UHI intensity in August 2039 for Downtown Austin Plan scenario and the proposed scenario (see figure 25) shows that in the new scenario, the average UHI intensity is higher than the condition existing in 2020 by 1° K, due to the increase in urban density with new constructions. However, a decrease of 1° K in the UHI intensity is seen when more open spaces are added to the 2039 plan. Also, the average UHI magnitude in January decreases less than 1° K in this scenario (see figure 26). Compared to configuration one, the same trend of UHI magnitude change throughout the day is seen for both months of August and January.

Figure 23. Average Urban Heat Island Intensity - Configuration 3 - August. (Generated by UWG)

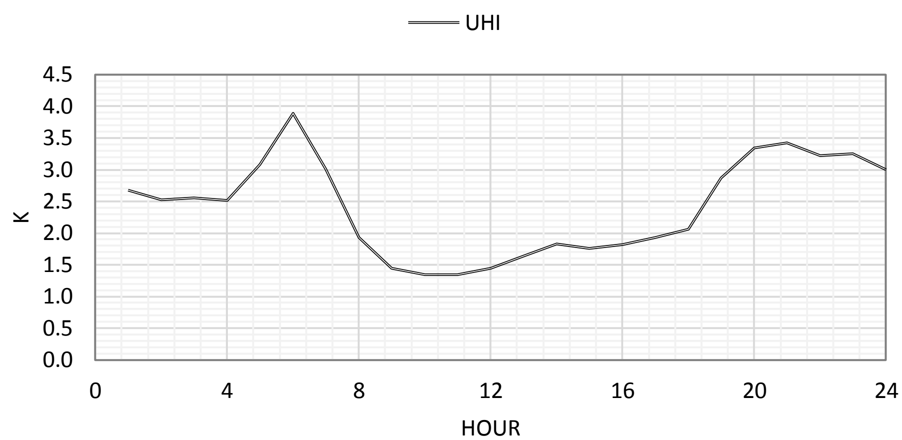


Figure 24. Average Urban Heat Island Intensity - Configuration 3 - January. (Generated by UWG)

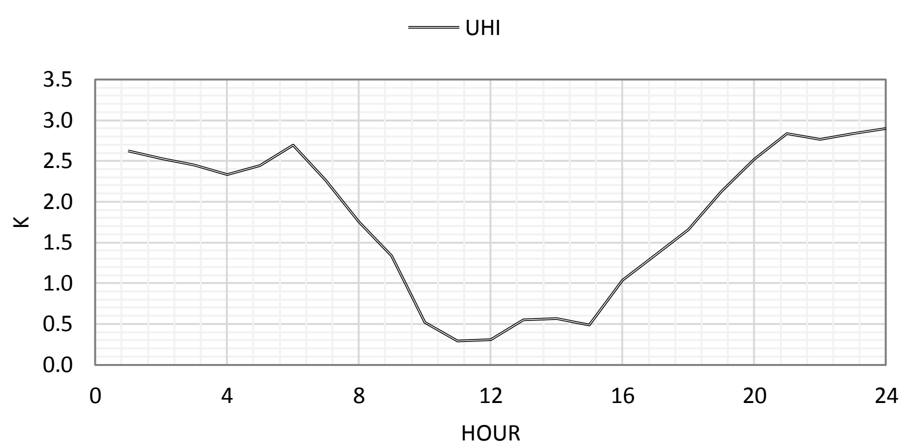


Figure 25. Comparison Between Average Urban Heat Island Intensity- August - Configuration 2 & 3. (Generated by UWG)

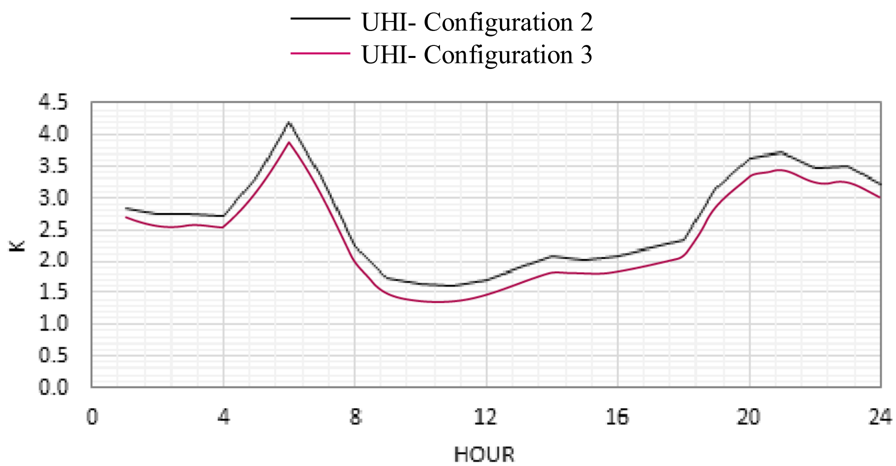


Figure 26. Comparison Between Average Urban Heat Island Intensity – August - Configuration 2 & 3. (Generated by UWG)

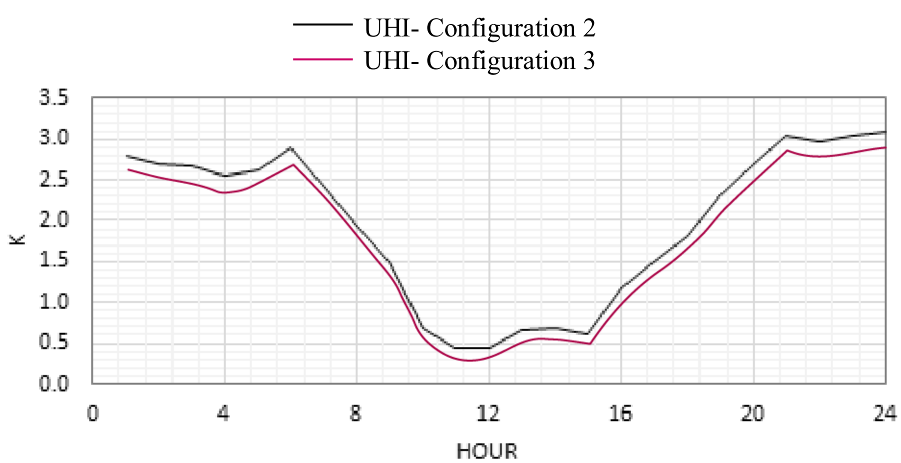


Figure 27 and Figure 28 illustrate UHI variation for August and January 2039 in configuration three.

Figure 27. Variations in Urban Heat Island Effect - Configuration 3 - August. (Generated by UWG).

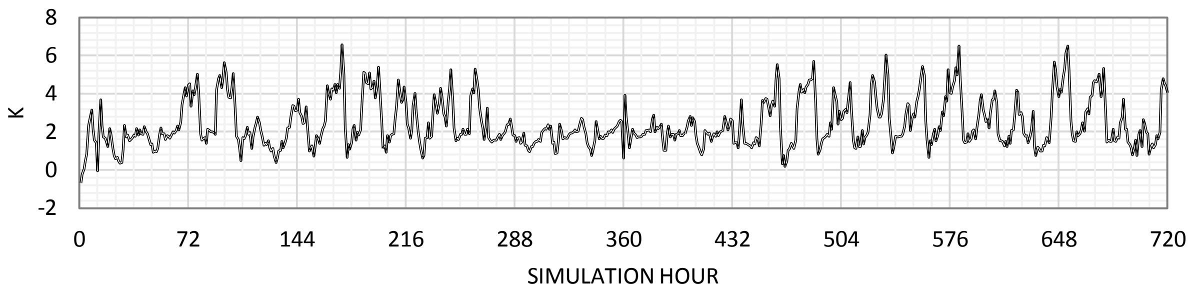
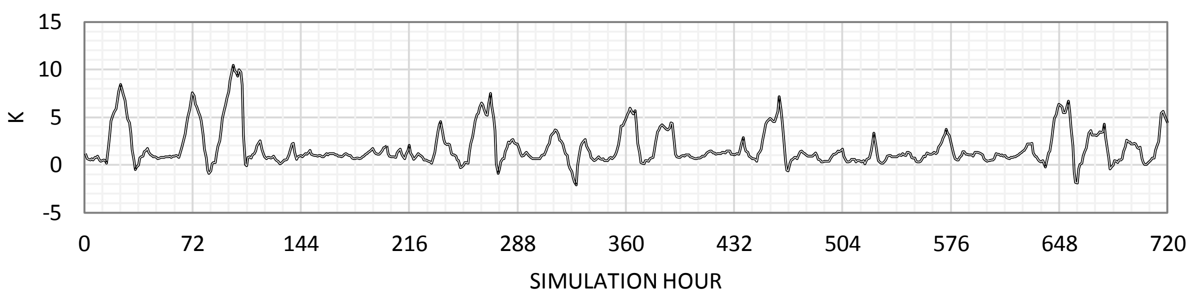


Figure 28. Variations in Urban Heat Island Effect - Configuration 3 - January (Generated by UWG).



Although the new proposal decreased the downtown HUI average intensity, there is not a significant change in its variation over the months of August and January in 2039 (see figures 29 & 30).

Figure 29. Comparison Between Variations in Urban Heat Island Effect- August - Configuration 2 & 3. (Generated by UWG)

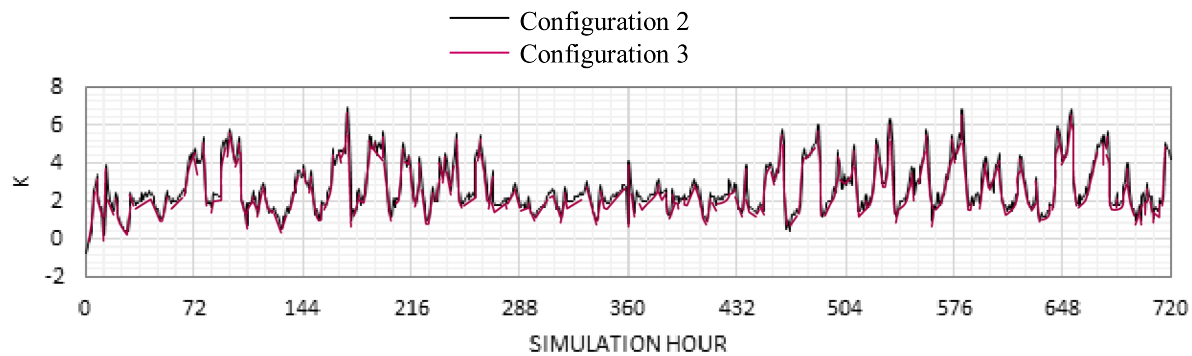
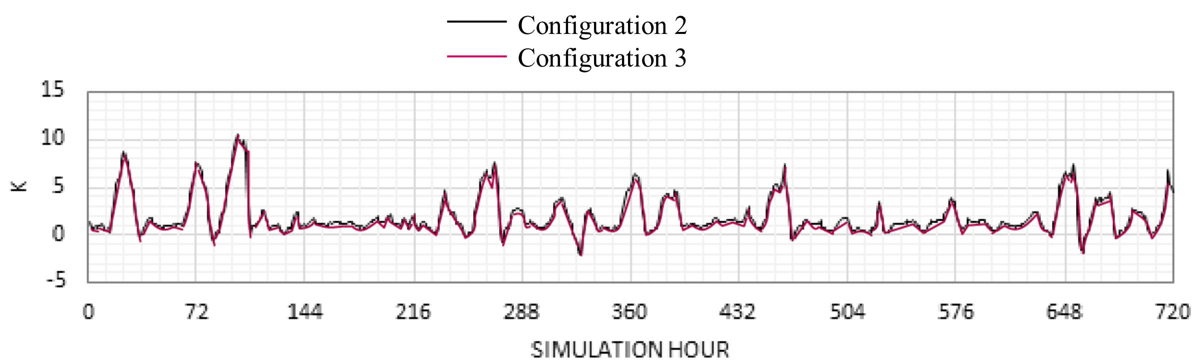


Figure 30. Comparison Between Variations in Urban Heat Island Effect- January - Configuration 2 & 3. (Generated by UWG)



In both cases there are only a few peaks that are slightly lower than the Downtown Austin Plan proposal. This indicates that despite the modification of the urban fabric, the air temperature difference between Austin's urban core and rural areas would still maintain a wide range while the average UHI intensity would decrease by 1 K, which is half of the initial change of 2° K between years 2020 and 2039. I should note that, as was previously mentioned, UWG is not capable of capturing site-specific microclimate effects and it measures the general UHI over the site area; therefore, I was not able to find areas with the highest UHI intensity to modify the urban fabric. For instance, as it is shown in Figure 13, Downtown Austin future development is not distributed equally over the whole 1000 acres, and therefore UIH magnitude is higher in more dense and developed areas—those which should include more open spaces.

Chapter 6: Discussion and Conclusion

This research aimed to study the impact of future development of Downtown Austin on the current level of Urban Heat Island (UHI) effect. Downtown Austin Plan (DAP) was envisioned in 2011 to address the challenges that the downtown area faces due to the rapid growth and influx of new residents. The DAP envisions a dense downtown area and a series of potential new constructions on about 150 acres of the downtown area by the end of the year 2039.

The UHI phenomenon has been among the City's growing concerns since 2000, when the construction of high-rises and towers started taking place in Austin's CBD. As a result, a commission was formed to study and implement the recommendation to mitigate Austin UHIs. Currently, the City of Austin recommends six strategies to mitigate UHI effect. Although some of these recommendations, like having reflective roofs, have become codes in past years and do have a positive impact, most of the City's strategies towards mitigating UHI revolve around residents and individuals rather than providing regulations and rules for the future developments being rapidly built.

Strategies recommended by the Austin Urban Heat Island Initiative (UHII), like those mentioned by the U.S. Environmental Protection Agency (EPA), mostly ignore the key role design parameters such as building height, H/W ratio, built density, and general urban form play in both reducing or intensifying UHIs and in broadly affecting urban climate. Design parameters become even more important when we note that strategies like adding more green and vegetated areas, which are the most recommended and popular mitigation strategies, are not applicable in all locations.

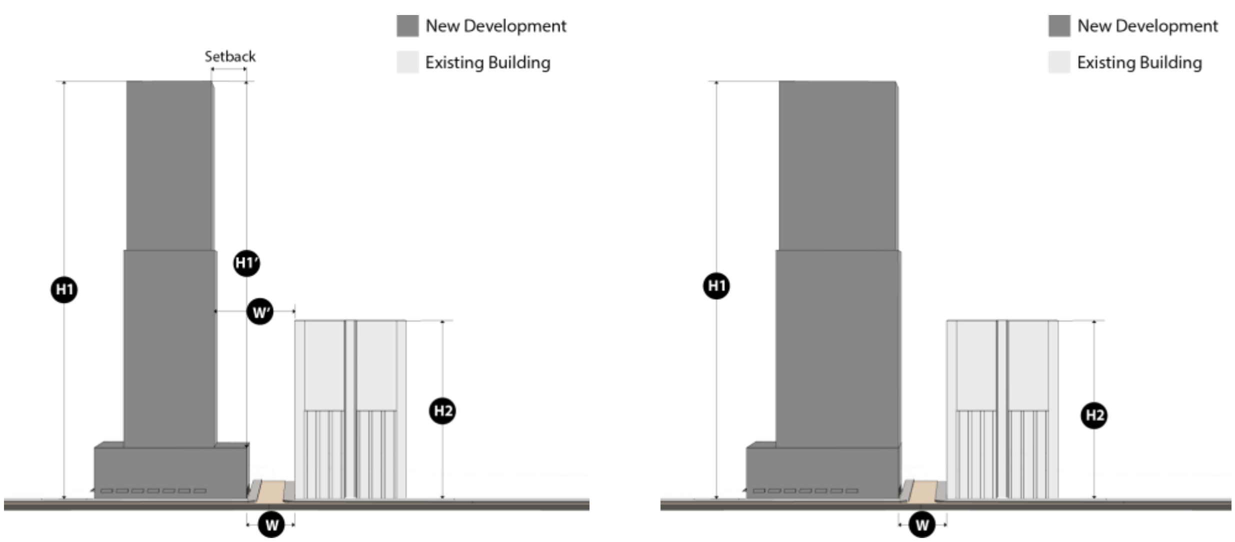
In order to consider design parameters and modify them to improve future urban climate, which is affected by products of rapid urbanization (i.e. UHIs), urban planners and designers need a tool to predict the impact of their plans and design on urban climate. A few tools are currently available, such as Computation Fluid Dynamics (CFD) or numerical simulation tools. However, they have high computational cost or limited spatial and temporal scope. Urban Weather Generator, meanwhile, is a simple model developed by Bueno et al. (2012) at Massachusetts Institute of Technology. UWG uses meteorological information gathered from a rural weather station and simulates canopy level urban air temperature. This tool is publicly accessible and computationally efficient.

Consequently, UWG was used in this study to simulate three sets of configurations for Downtown Austin. Model configurations were set as: 1) Downtown Austin in 2020; 2) Downtown Austin in 2039 (at the end of the implementation of DAP); 3) Downtown Austin in 2039 with 1/8 of the urban fabric proposed in DAP being replaced with open spaces. The simulation showed that, if Downtown Austin develops following the DAP, UHI intensity will increase over 2° K during the month of August 2039—the month with the highest air temperature throughout the whole year-long period. On the other hand, if the building density suggested by DAP is reduced to 87% of the initial proposal, the increase in the average UHI intensity is reduced to 1° K over 20 years.

This study indicates that modifying design parameters is of key importance in mitigating UHIs and protecting/improving the future urban climate, which further demonstrates the need to use prediction tools and techniques to assess the impact of future development on urban climate and UHI magnitude. This analysis should be conducted in early stages of the design process to give urban planners and designers the opportunity to modify their plans, strategies, and design. As Downtown Austin is still in the early phases of the implementation of the Downtown Plan, the City should investigate the impacts of parameters such as building height, FAR, and streets width on UHI and adopt appropriate regulations and codes.

Although future development and high density in Downtown Austin is unavoidable, their negative impacts can be moderated through urban planning and design efforts. For instance, the DAP proposed density bonus program defines no building height limitation for a great percentage of the downtown area. As the building height and urban form are one of the main parameters in the formation of UHIs, the City of Austin should put a limitation on how high buildings are constructed. In addition, a required setback from the sidewise vertical line for the upper floors of high-rises and towers helps to widen up the air flow path and enhance the turbulence (see Figure 31). Additionally, the extended lower levels and podiums protect pedestrians from the accelerated wind and downwash that occurs at the ground level of tall constructions. Also, as Shishegar (2013) argues, the variety in building heights, in this case, leads to better ventilation in the urban canyon.

Figure 31. Design Parameters Modification. (Author, 2017).



In the UWG model, as the sensitivity analysis showed, the façade-to-site ratio has a positive correlation with UHI magnitudes. With the required setback, the upper level perimeters reduce façade-to-site ratio, thus decreasing the UHI intensity. As Oke (1988) states, the average urban geometries are measured by two factors: aspect ratio and building density. With the required setback, both aspect ratio and building density decrease. Consequently, as the higher levels of the street canyon get wider it leads to a better mixing of air and as a result, airflow improves within the street (Shishegar, 2013). While considering these improvements, it should be noted that high-rises are not necessarily negative elements in an urban area. According to Priyadarsini and Wong (2005), when the wind flow is parallel to the urban canyon, locating a few numbers of high-rises in the canyon improves the air flow within the street. However, the number of towers, their distribution within the urban area to have enough open spaces, and also height limitations as well as aspect ratios should be taken into considerations in urban planning and building regulations.

The process of simulating the future development of a city or neighborhood and predicting the UHI that will possibly form over that area is valuable not only for existing developed cities but also for the rural regions which are transitioning from suburban forms to a more urbanized morphology. Including UHI mitigation strategies, with a greater emphasis on urban forms and geometries, in the city codes and regulation at the early stages of that transition, not only is helpful in mitigating the future UHI effect but also might prevent the formation of heat islands. When a city like Austin is growing rapidly, the surrounding small towns and rural areas also beginning to grow. One of the contributing factors to the growth of a city’s surrounding region is the immigration of those residents who were not able to live in the more expensive urban dwellings, as well as the concentration of industries or tech companies in those surrounding towns. For instance, as Austin is growing fast, the City of Round Rock located just north of Austin is also growing. Most of the tech companies and start-ups that have moved to Austin recently are headquartered in Round Rock. However, the UHI effect is not taken into consideration in the Round Rock Downtown Master Plan (2010) and is only mentioned while the plan talks about parking lots and pavements.

As we consider the causes, impacts, and mitigation strategies of UHIs, it is necessary to consider the future in addition to recognizing the existing conditions. Cities are growing rapidly as more people move from rural to urban areas. There should be an effort to provide more time and cost efficient simulation tools and techniques to help urban planners and designers model future UHIs and provide adequate mitigation strategies. In addition, small towns located near developing cities should also develop UHI mitigation strategies; although they may grow as quickly as the core city, they have more flexibility in terms of developing in-depth mitigation solution and instituting urban design parameters and urban fabric modifications, including requirements for road and building façade materials, building densities, and height limitations.

Appendices

Appendix A

Emerging Project Building Heights

Number	Proj_Name	Height (Feet)	Stories	Completion	Status
R38	The Shore	257	22	2008	Complete
R60	Seven Apartments (aka 7rio)	250	24	2015	Complete
C42	Hotel Van Zandt	240	16	2015	Complete
C87	5th and Colorado	227	18	2016	Complete
R9	AMLI on 2nd	225	18	2008	Complete
TC1	Blackwell-Thurman Criminal Justice Center	204	11	2000	Complete
R81	Rise	200	21	2016	Complete
R84	Whitley	195	18	2013	Complete
R82	Gables Park Tower	194	18	2014	Complete
C60	Hyatt Place	191	17	2013	Complete
C2c	Shoal Creek Walk, Building 1	180	18	2017	Under Construction
R20	Austin City Lofts	180	14	2004	Complete
C75	IBC Bank Plaza	179	13	2014	Complete
R18	The Plaza Lofts	174	12	2002	Complete
C25	Hampton Inn and Suites	166	16	2002	Complete
R64	Sabine on Fifth	155	10	2008	Complete
R5.1	The Milago on Town Lake	142	13	2006	Complete
C32	Residence Inn / Courtyard by Marriott	141	12	2006	Complete
R11	Brown Building	137	10	1999	Complete
C2b	Austin Market District (Whole Foods Block)	136	7	2005	Complete
R1	The Nokonah	135	11	2002	Complete
R54	Brazos Place Condominiums	134	14	2007	Complete
O5	Texas Association of Counties	132	8	2003	Complete
C41	1108 Lavaca	126	9	2008	Complete
R3	AMLI Downtown	106	7	2004	Complete
R89	The Millennium Rainey	99	8	2016	Complete
C102	Hyatt House Hotel	98	910	2017	Under Construction
R2.1	Gables Park Plaza	86	8	2010	Complete
C54	5th and Brazos	83	8	2015	Complete
C2i	Shoal Creek Walk, Building 2	73	5	2019	Planned
A5	New City Hall and Public Plaza	65	4	2004	Complete
O6	Trinity Center (Texas Retired Teachers Association)	60	4.5	2004	Complete
C90	Rainey St. Hotel (formerly Kimber Modern)	56	4	2016	On Hold
O13	First Baptist Church Ministry Center & Parking Garage	49	5	2010	Complete

Emerging Project Building Heights

Number	Proj_Name	Height (Feet)	Stories	Completion	Status
R4	Red River Flats	48	4	2008	Complete
C37	Sovereign Bank	30	2	2005	Complete
C47	Block 52		40	2018	On Hold
R92	Trinity Place Tower		39	2018	On Hold
R109	Third & Colorado		39		Planned
C101	Austin Proper Hotel & Residences		32	2018	Under Construction
R101	48 East		31	2019	Planned
C56	Green Water Block 185		30	2018	Planned
R105	721 Congress / The Avenue		30	2019	Planned
C96	6th and Nueces Hotel site		28	2017	Planned
C108	Marriott Hotel at Cesar Chavez		27		Planned
C105	405 Colorado		25		Planned
UT5	New UT System Administration Building		19	2017	Under Construction
C97	Homewood Suites at East Avenue		14	2017	Under Construction
C115	1400 Lavaca		12	2019	Planned
C83	Holiday Inn Express		10	2016	Complete
C92	Hotel Indigo		10	2016	Complete
R96	The G Austin		9	2014	Complete
US1	Federal Courthouse		8	2012	Complete
C71	Hampton Inn & Suites at The University/Capitol		8	2012	Complete
C2f	Austin Market District, South Block Ph. II		7		Complete
TC3	Travis County Ronnie Earle Building		7	2017	Under Construction
C4b	Computer Sciences Corp (CSC) – Block 4		6	2001	Complete
C4a	Computer Sciences Corp (CSC) – Block 2		6	2001	Complete
C52	Cirrus Logic		6	2012	Complete
C94	Cirrus Logic Phase II		6	2015	Complete
R108	West Sixth Micro Project		6		Planned
R13	Avenue Lofts		5	1999	Complete
R16	404 Rio Grande		5	2004	Complete
C35	ABC Bank		5	2007	Complete
R53	Park West Avenue		5	2009	Complete
R72	West 15th Street Condos		5	2015	On Hold
C109	Episcopal Church Block 87		5	2019	Planned
R88	Capital Studios		5	2014	Complete

Emerging Project Building Heights

Number	Proj_Name	Height (Feet)	Stories	Completion	Status
A4	Austin Resource Center for the Homeless (ARCH)			2004	Complete
C26	CBD Restaurants			2001	Complete
A9	Convention Center Parking Garage and Central Chilling Plant			2006	Complete
T6	Lance Armstrong Crosstown Bikeway			2012	Complete
T4b	Pfluger Bridge Extension Project			2011	Complete
A10	Republic Square, Phase I			2010	Complete
T7	Second Street District Streetscape Improvements, Phase II			2011	Complete
O7	Mexic-Arte Museum			2019	Planned
C2d	Austin Market District (North Block)			2006	Complete
O8	Joseph and Susanna Dickinson Hannig Museum Renovation			2010	Complete
O10	Texas Municipal Retirement System			2005	Complete
C38	Third and Trinity			2006	Complete
CM2	CMTA MetroRail			2010	Complete
A1	Austin Energy Seaholm Substation			2017	Under Construction
CM3	Future Connections Study			2008	Complete
O11	Austin Music Hall			2008	Complete
O12	Ballet Austin Butler Dance Education Center			2007	Complete
C48	Stubb's Green Building			2014	Complete
ACC1	ACC Parking Garage				Complete
C57	1300 Guadalupe			2010	Complete
A14	New Central Library			2017	Under Construction
A15	Mexican-American Cultural Center (MACC) Education Building			2010	Complete
R70	1306 West Avenue			2017	Under Construction
O17	Arthouse at the Jones Center Expansion			2010	Complete
C67	Hospital Housekeeping Systems Inc.			2013	Complete
A17	Republic Square, Phase II			2017	Under Construction
C72	Firehouse Hostel & Lounge			2013	Complete
C2g	7th & Lamar (North Block, Phase II)			2014	Complete
T6a	Lance Armstrong Crosstown Bikeway (downtown segment)			2012	Complete
UT6	UT System - Block 71				Planned
A18	Intake and Utility Buildings			2019	Planned
C78	Texas Public Policy Foundation Office Building			2015	Complete

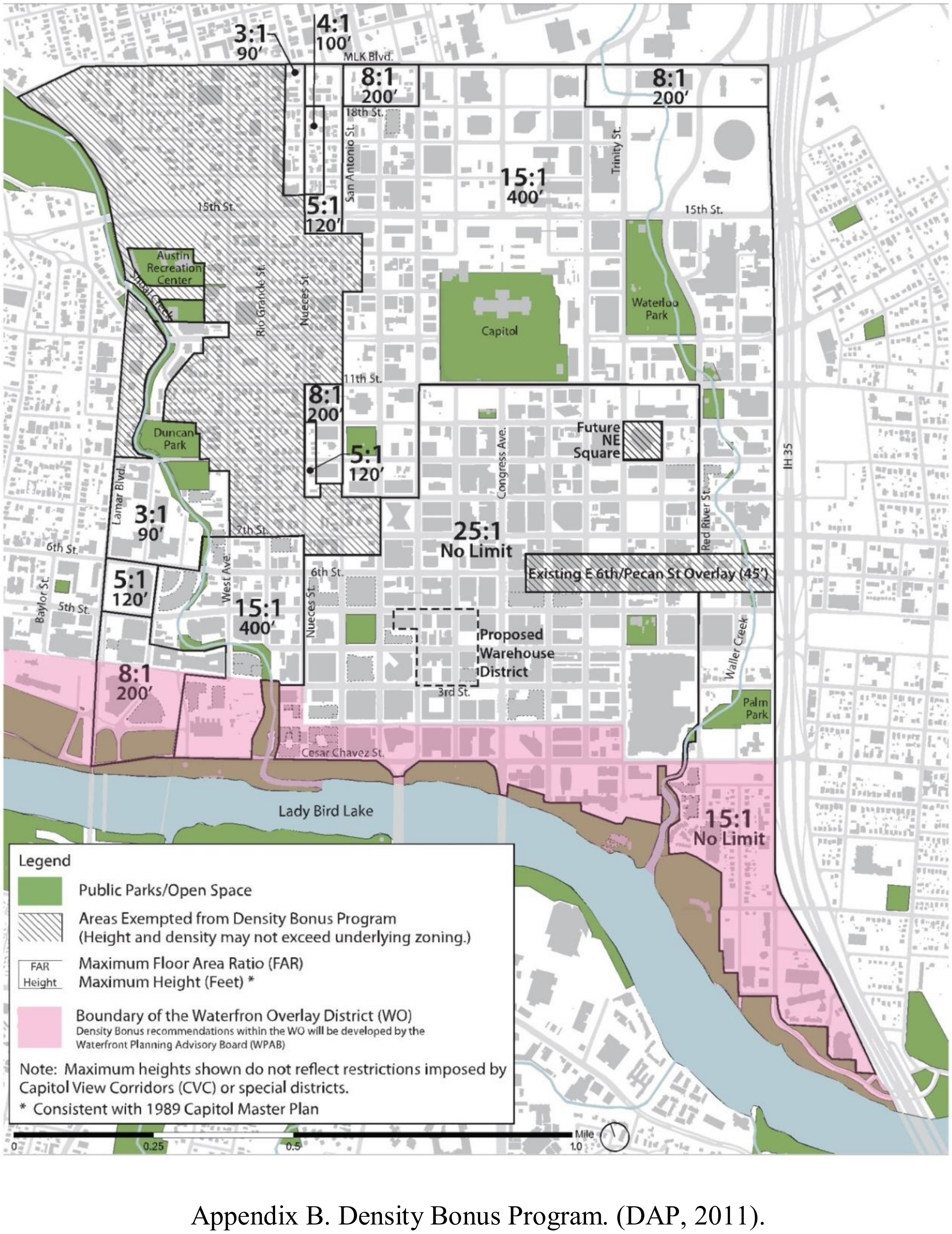
Emerging Project Building Heights

Number	Proj_Name	Height (Feet)	Stories	Completion	Status
C80	501 Congress		5	2015	Complete
O21	Texas PTA		5	2015	Complete
R102	908 Nueces Condominiums		5	2017	Under Construction
R17	Gables West Avenue		4	2001	Complete
C17	1001 Congress		4	2002	Complete
C58	Starr & Buttrey Buildings		4	2012	Complete
C86	1303 San Antonio		4		On Hold
R107	East 9th Street Multifamily		4		On Hold
R12	Brazos Lofts		3	1999	Complete
C44	CITI Bank		3	2007	Complete
C2h	4th & Lamar (Austin Market District, South Block Ph. III)		3	2013	Complete
R80	904 West		2	2010	Complete
C84	Cirrus Logic Research Facility		2	2014	Complete
C2a	Austin Market District (South Block)			2000	Complete
C24	Phillips Building			1999	Complete
C10	Grove Drug Building			1999	Complete
A6	Convention Center Expansion			2002	Complete
A8	Mexican-American Cultural Center (MACC)			2007	Complete
T2	Lone Star (Austin-San Antonio Corridor) Rail			2017	On Hold
C11	Intercontinental - Stephen F. Austin Hotel			2000	Complete
C12	Landmark Office Complex			2000	Complete
C13	Time Warner Cable News 8 Studio			1999	Complete
S2	Robert E. Johnson State Office Building			1999	Complete
S3	Bob Bullock Texas State History Museum			2001	Complete
S4	State of Texas parking structures			1999	Complete
C14	The Texas Broadcast Center			1999	Complete
C15	GSD&M Expansion			1999	Complete
O1	American Youthworks			1999	Complete
C16	1011 San Jacinto			1999	Complete
T3	Congress Avenue Streetscape Beautification			2000	Complete
T4a	James D. Pfluger, FAIA Bridge			2001	Complete
C19	Extended StayAmerica Hotel			2000	Complete
T5	Waller Creek Flood Diversion Tunnel			2017	Under Construction
C23	Texas Trial Lawyers Association			2000	Complete

Emerging Project Building Heights

Number	Proj_Name	Height (Feet)	Stories	Completion	Status
C79	Block 19				Land Sale
C81	Cesar Chavez and Red River (southeast corner)				Land Sale
O22	Dell Seton Medical Center at The University of Texas			2017	Under Construction
UT7	Dell Medical School Health Learning Building			2016	Complete
UT8	Dell Medical Health Transformation Building & Garage			2016	Complete
UT10	Dell Medical Health Discovery Building			2017	Under Construction
C88	The Riley			2017	Under Construction
C98	4th & Red River				Land Sale
CM5	Downtown MetroRail Station Expansion				Planned
C100	1705 Guadalupe			2015	Complete
S5	State office building #1				Planned
S6	State office building #2				Planned
A19	Sabine Street Promenade			2020	Planned
O23	Central Health Brackenridge Campus Redevelopment				Planned
O17	The Contemporary Austin – Jones Center Renovation			2016	Complete
O24	Texas Association of Counties				On Hold
R106	Sutton Villas site			2019	Planned
TC4	Travis County probate court and clerks offices				Planned
O25	Waterloo Park makeover				Planned
R113	Texas Motor Transport				Planned

Appendix B



Appendix B. Density Bonus Program. (DAP, 2011).

Appendix C

7/29/2017 ArcGIS - Green Roofs in Austin, Texas

Green Roofs in Austin, Texas

This is a map is Green Roofs located in Austin, Texas. The data comes from the Green Roofs Advisory Group and the map is maintained by Austin Energy.

Esri, HERE | Austin Community College, Esri, HERE, Garmin, INCREMENT P, NGA, USGS

http://www.arcgis.com/home/webmap/print.html

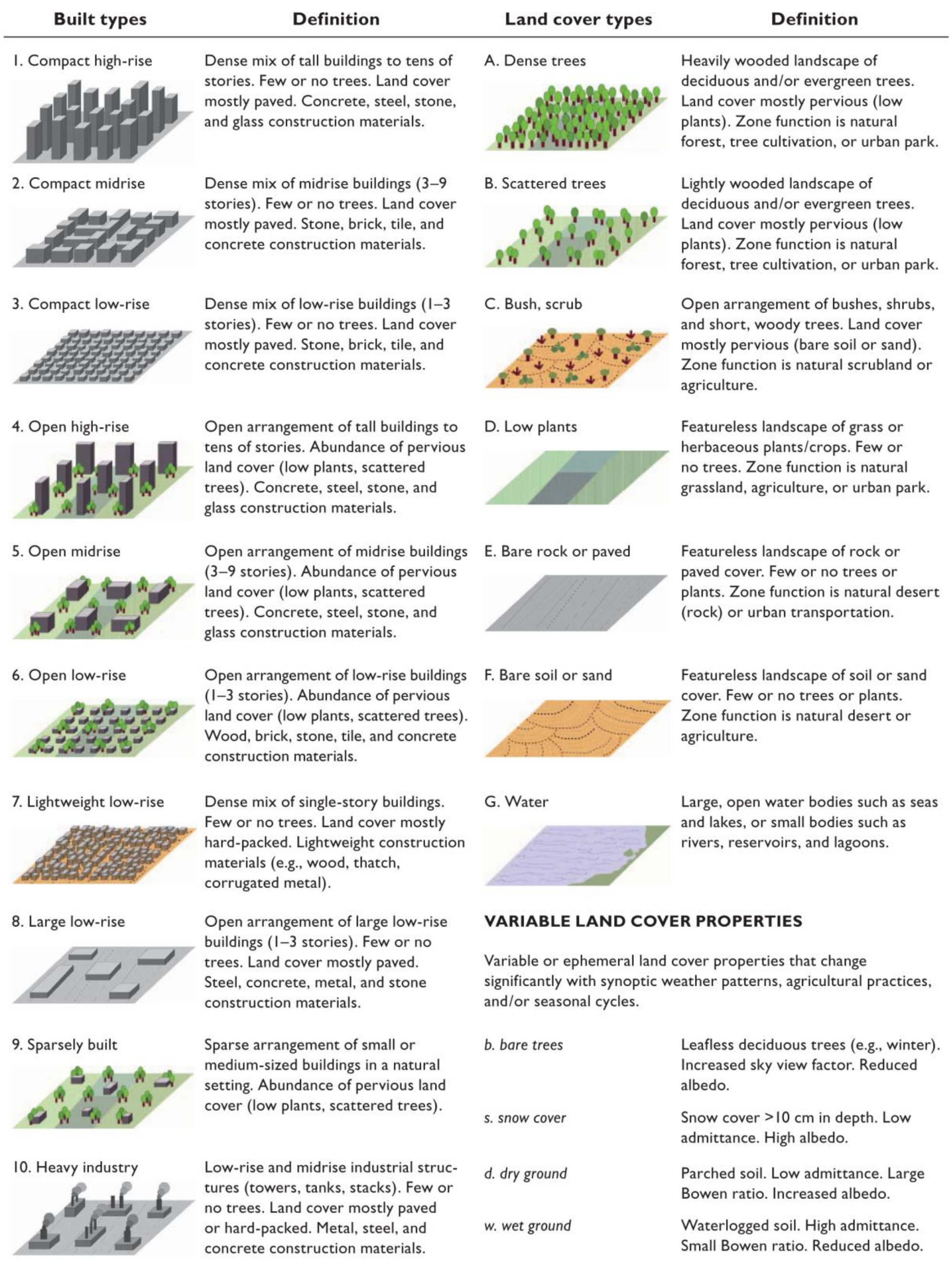
By Niloufar Karimipour- July 2017

Appendix D

Parameter	Definition	Range/unit	Recommended Setting
Vegetation coverage	The amount of vegetation on surfaces, such as green roof, grassy lawn, and vine-covered wall.		Green roof 1, concrete wall 0
Average building height	Average building height in the urban area, normalized by building footprint	m	Stewart & Oke's study, (20120)
Site coverage ratio	Describes how close buildings are built in the city. Defined by ΣAbldg / Asite ,	0-1	-
Facade-to-site ratio	Ratio of wall area to the urban plan area. Used to calculate canyon height and thus solar radiation received by building facade	0-1	-
Tree coverage	Amount of tree coverage in the urban area, includes those on the side streets	0-1	-
Sensible anthropogenic heat, other than from buildings	Defines amount of heat released to urban canyon as sensible heat, mostly from traffic.	W/m2	10-20 W/m2
Neighborhood characteristic length	Radius of the urban area being modeled (√site area)	m	-
Albedo of vegetation	Ratio of reflected radiation from the vegetation surfaces to incident radiation upon them	0-1	0.25
Daytime boundary layer height	Height of the urban boundary layer during daytime.	m	700
Nighttime boundary layer height	Height of the urban boundary layer during nighttime.	m	80
Latitude	Latitude of the reference site	[o]	-
Longitude	Longitude of the reference site	[o]	-
Temperature measurement height	The height at which temperature is measured on the weather station	m	2
Wind measurement height	The height at which wind speed is measured on the weather station	m	10
Simulation start month	Start month of the simulation*	1-12	-
Simulation start day	Start date of the simulation*	1-31	-

Appendix D. Urban Weather Generator Parameters Definition & Values. (Urban Weather Generator, n.d.).
*UWG will morph the weather file for only the selected period.

Appendix E



Built types	Definition
1. Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.
2. Compact midrise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
3. Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
4. Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
5. Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
6. Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.
7. Lightweight low-rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).
10. Heavy industry	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.

Land cover types	Definition
A. Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
B. Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
C. Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
D. Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
E. Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
F. Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.

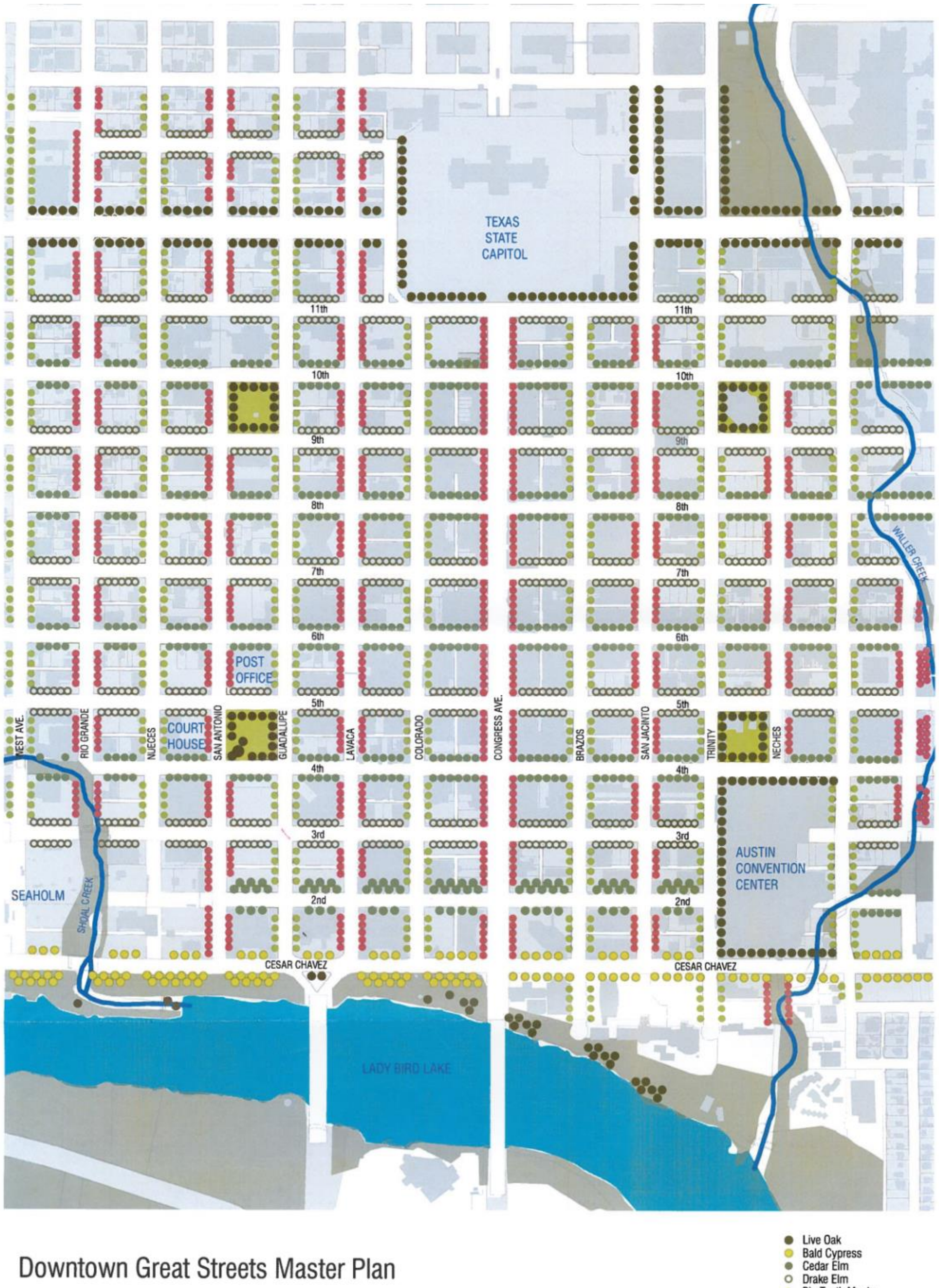
VARIABLE LAND COVER PROPERTIES

Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.

b. bare trees	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
d. dry ground	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

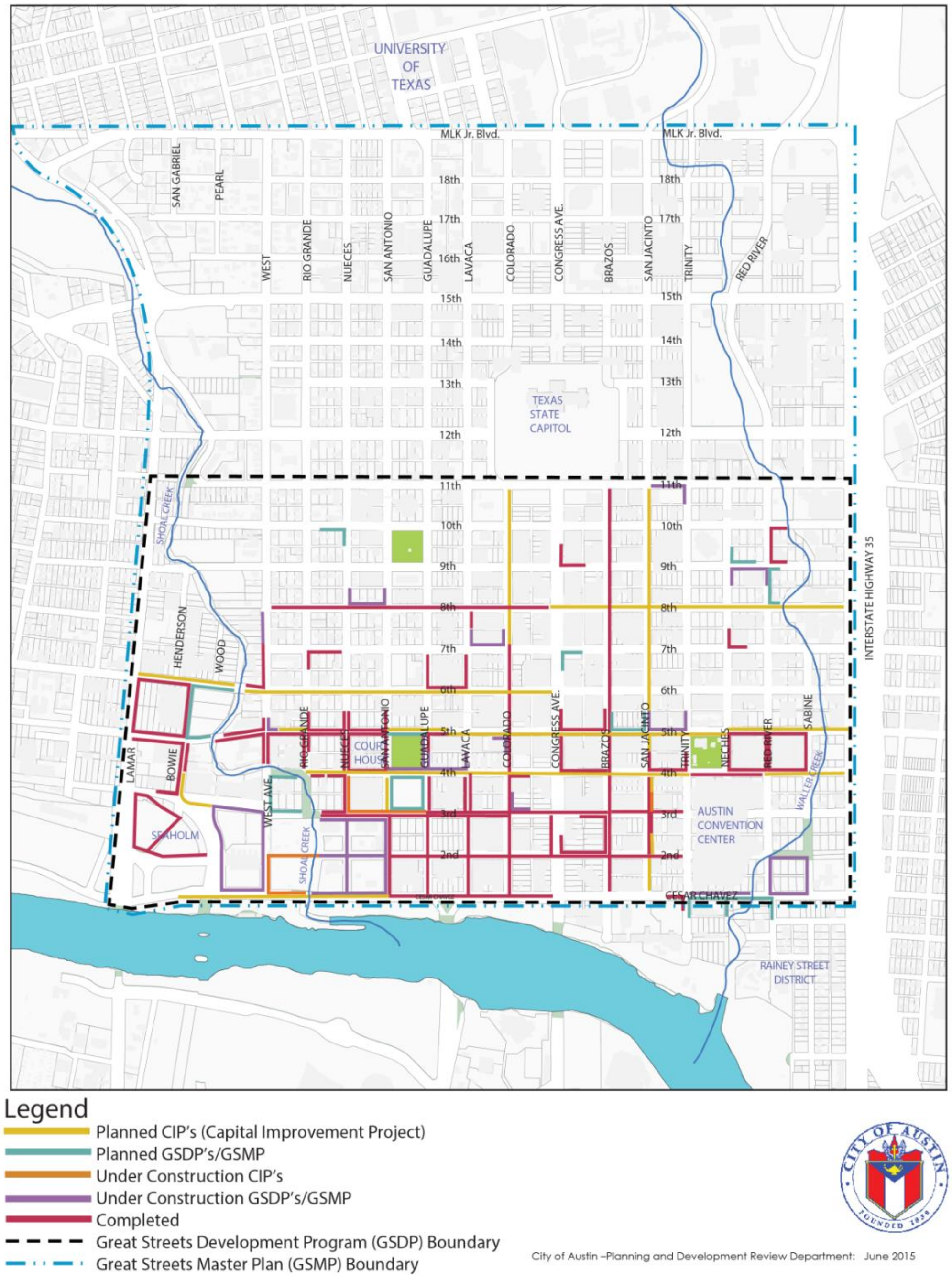
Appendix E. Urban Classifications and Definitions. (Stewart & Oke, 2012).

Appendix F



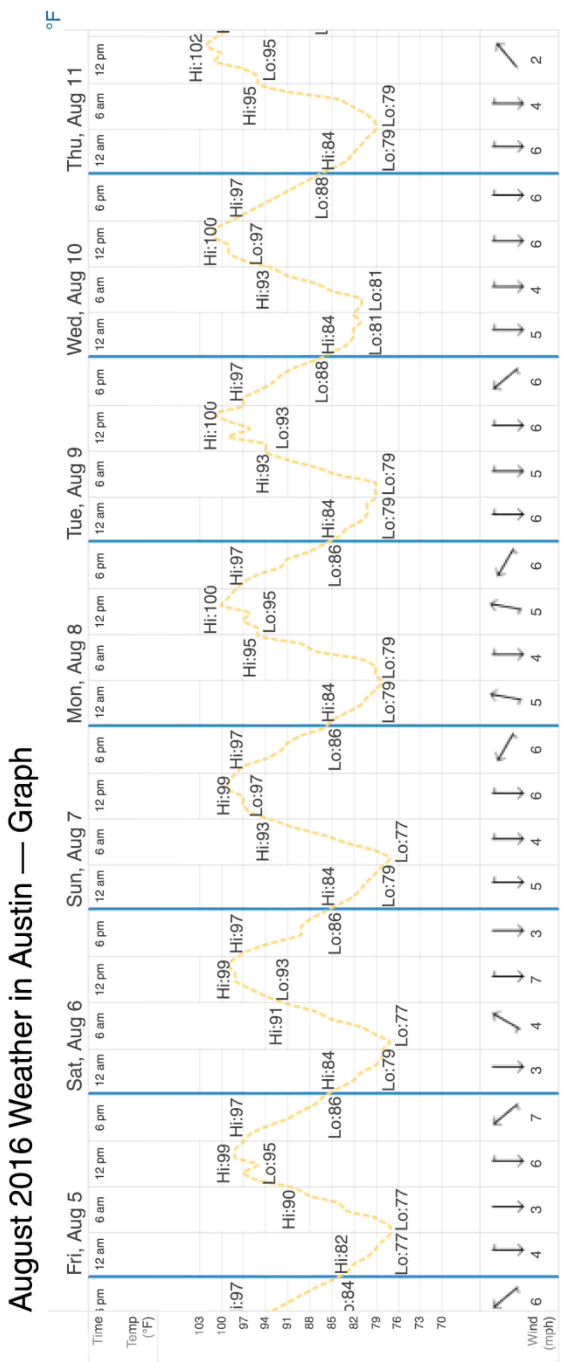
Appendix F. Street Scape Planting and Accessories. (Obtained from City of Austin Staff).

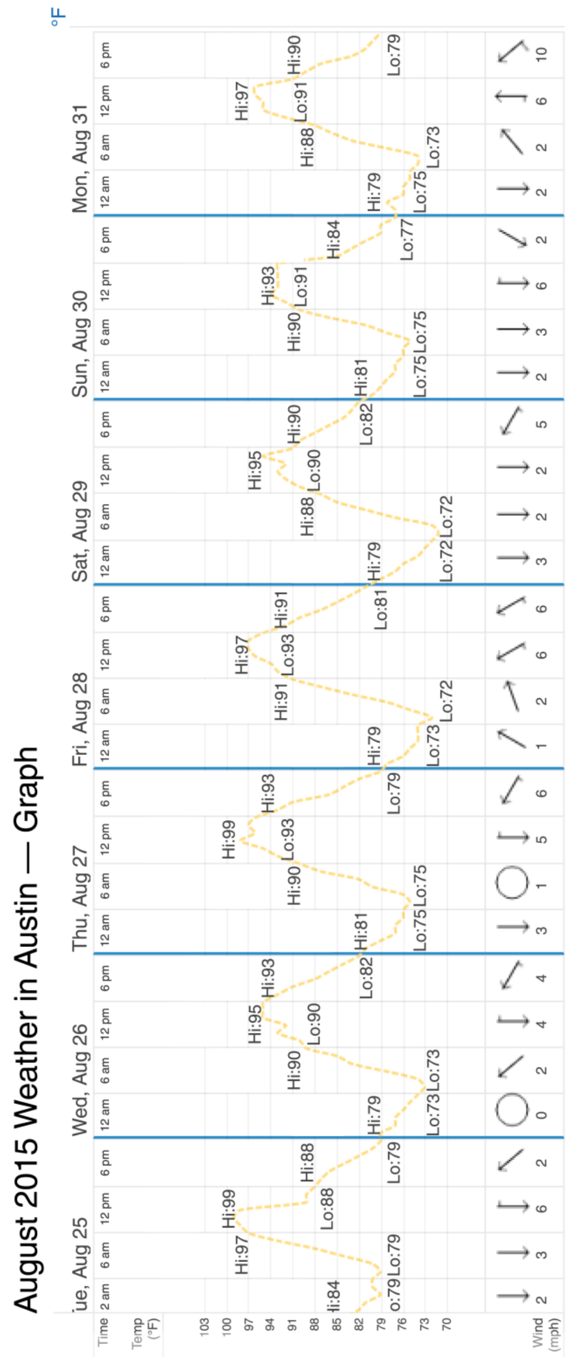
Appendix G



Appendix G. Great Street Master Plan Implementation. (Obtained from City of Austin Staff).

Appendix H





Appendix H. Austin daily temperature in early August 2016 and 2015. (Time and Date, n.d.)

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