Cityscapes, Climate, and Mental Health: Prioritizing Thermal and Mental Wellbeing in the Design of Cities

by

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ABSTRACT

Urban climate conditions are the physical manifestation of formal and informal social forces of design, policy, and urban management. The urban design community (e.g. planners, architects, urban designers, landscape architects, engineers) impacts urban development through influential built projects and design discourse. Their decisions create urban landscapes that impact physiological and mental health for people that live in and around them. Therefore, to understand possible opportunities for decision-making to support healthier urban environments and communities, this dissertation examines the role of neighborhood design on the thermal environment and the effect the thermal environment has on mental health. In situ data collection and numerical modeling are used to assess current and proposed urban design configurations in the Edison Eastlake public housing community in central Phoenix for their efficacy in cooling the thermal environment. A distributed lagged non-linear model is used to investigate the relative risk of hospitalization for schizophrenia in Maricopa County based on atmospheric conditions. The dissertation incorporates both an assessment of design strategies for the cooling of the thermal environment and an analysis of the existing thermal environment's relationship with mental health. By reframing the urban design of neighborhoods through the lens of urban climate, this research reinforces the importance of incorporating the community into the planning process and highlights some unintended outcomes of prioritizing the thermal environment in urban design.

DEDICATION

To Leah, who has become my biggest supporter and fan. Your steadfast support has been vital to achieving the goal of writing a dissertation in the middle of a pandemic.

To the residents of the Edison Eastlake neighborhood, though many may never see this document, their experiences help to shape and motivate this work to be something that is beneficial to the community, not just to academics. They have informed and motivated my research to provide actionable information to communities that historically have been unable to enact agency over their environment and surroundings. May this work be used to ensure future care for the thermal environment of Edison Eastlake.

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TABLE OF CONTENTS

CHAPTER Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

Figure Page

CHAPTER 1

INTRODUCTION

1.1 Introduction

Cities and their subsequent urban climate conditions are the physical manifestation of formal and informal social forces of design, policy, and urban management. Planners, architects, urban designers, landscape architects, and engineers all have a role in shaping urban design through influential built projects, policy, and design discourse. Their decisions create urban landscapes that impact physiological and mental health for people that live in and around them. Modern fields of research and practice in design emerged in response to 19th century public health emergencies of industrial cities (e.g. disease outbreaks, sanitation, and pollution exposure), in most cases centered on the physiological health of city dwellers. Although long acknowledged as an impact dating back to Frederick Law Olmsted, research is only now providing stronger empirical evidence of urban landscapes' impact on mental health. Thus, scholarly research is revisiting the role of the design community in creating better urban landscapes to support mental health. One understudied intersection of urban landscapes and mental health is the role that urban climate (e.g. thermal and air-quality environments) play in triggering of mental disorders. This knowledge gap is unsurprising given the difficulty in obtaining detailed data (and metadata) around mental disorders such as schizophrenia as well as the difficulty in identifying causality of mental health disorders from environmental conditions. Adding to this gap, the field of urban climate design and management or the intentional design of urban microclimates for more comfortable thermal spaces is still in its early stages compared to responses for other environmental hazards such as stormwater. Current thinking about urban climate design might be in a similar phase of conceptualization as stormwater management was in the early part of the 20th century (Hamstead et al., 2020). In the 1930s, Gilbert White shifted society's worldview of flooding, reframing the societal impacts of flooding not as an 'act of nature' from the hazard itself, but rather as a consequence of human planning and design decisions to either build in flood plains or create vast landscapes of impervious surface that have amplified flooding (Rome, 2001). Today, I seek to similarly reframe extremely hot landscapes as human amplified disasters for both physiological and mental health impacts.

For cities, recent urban climate initiatives are mainly focused on the reduction of the physical contributions of the urban heat island (UHI), such as modifying urban infrastructure to minimize air and surface temperature, while leaving out other important human-centered experiential impacts from heat. The UHI phenomena, also known as urban-induced warming, has been scientifically documented since the first half of the 19th century (Howard, 1833). Yet, it is only since the 1960s that urban climate research and design practice has begun to take elementary steps toward addressing the hazard. The UHI phenomena creates neighborhoods that are warmer than their less urbanized surroundings. In this process, the atmosphere is warmed by contact with buildings, pavement, and urban materials that efficiently absorb shortwave radiation, store the energy, and release that energy at night, warming the atmosphere near the ground (Oke et al., 2017). City officials, real estate developers, planners and designers struggle to adequately address urban-induced heating in planning and design projects. Working with the City of Tempe, AZ and Erie County, NY, Hamstead and colleagues (2020) found that practitioners often were unclear of their role in heat management or that managing heat was even part of their professional responsibility. Through discussions with practitioners in the two regions, they found that discourse overemphasized physical aspects of urban heat as a challenge at the detriment of a meaningful understanding of resident's thermal experience and social vulnerabilities. These attempts at addressing urban-induced warming are often directed toward a primary focus on the physical environment with a secondary interest in human physiological health and little concern for psychological well-being. Yet, the environment as well as the physiological health of a human also have significant impacts on the mental health of the individual and by extension social communities (Frumkin, 2003). In most cities, the inequitable distribution of heat hazards exposes some communities more than others to the psychological and sociological trauma from excessive heat exposure leading to climate injustice (Bolin et al., 2005; Harlan et al., 2013, 2006). The linkages between urban-induced warming and both individual and more collective neighborhood mental health were hinted at more than a century ago and while some research supports the possibility of these linkages, they have not been explicitly considered in the planning and design literature and practice.

Therefore, the objective of this dissertation is to connect urban design theory with the production of urban microclimates and current understanding of mental health crises, providing a roadmap for making urban climate and mental health a central responsibility for the design community. First, a broad discussion of the 19th century design movements that addressed what are often considered today urban climate challenges and their connection to human mental health. Next, in light of the history of heat riskscapes (Jenerette et al., 2011) or neighborhoods of high heat exposure, which create thermally inequitable landscapes and potentially community trauma, I discuss the Edison Eastlake neighborhood in Phoenix. Then in the body of this dissertation, I will consider how green infrastructure (e.g. trees and vegetation) can be one important strategy to address mental health using a case study in the city of Phoenix, Arizona.

Finally, I examine the impact the thermal environment has on mental wellbeing across the county using schizophrenia hospitalization data from Maricopa County.

This dissertation addresses how a better understanding of the interrelationships between urban infrastructure, urban climate, and mental health can provide better design pathways for healthier urban environments. Within this broader question are three research questions I seek to address: (1) how effective is ENVI-met (a micro-scale CFD model) at estimating the thermal environment of a hot arid neighborhood? (2) What is the impact of the city's redevelopment plans on the thermal environment of Edison Eastlake and what is the value of the designs for future neighborhood planning opportunities? And (3) what is the association of temperature and schizophrenia hospital admissions in an arid urban climate and how can we quantify the associated public health burden for Maricopa County?

1.2 Foundational Design Theory of Urban-induced Triggers for Schizophrenia

Contemporary Concepts on Green Infrastructure

One of the key aspects of urban infrastructure is the intentional manipulation of the natural environment to serve (and sometimes disserve) the human population (Cutter et al., 2014; McPhearson et al., 2016; Von Döhren and Haase, 2015). Urban infrastructure (biotic and abiotic) is developed through social and technological processes (Childers et al., 2015) and thus are endowed with all the politics, injustices, and complexities of any human system. Urban climatologists study the impacts of urban infrastructure on atmospheric conditions surrounding the urban development.

A contemporary approach of describing these impacts that ecosystems have on society is through ecosystem services or eco-services (Duraiappah et al., 2005). Ecosystems provide a host of societal benefits that are typically non-monetized and researchers commonly categorized them as provisioning, regulating, cultural, and supporting services. These services cover a wide variety of ecosystem impacts on society, from the resources society needs (provisioning), to the natural ability to handle the impacts of natural and anthropogenic disasters (regulating) (Duraiappah et al., 2005). This framework for considering the benefits of the ecosystem on human society, though the possibility for there to be burdens to human society from the ecosystem as well (Childers et al., 2015; Von Döhren and Haase, 2015). Eco-services are important to this discussion of urban design, thermal comfort, and mental wellbeing. The way in which eco-services or disservices are intentionally designed into city neighborhoods through social processes determine the extent of modifications to the atmosphere near the ground. Evidence is mounting that neighborhoods with abundant green infrastructure provide both climate regulation (i.e. increased thermal comfort) and cultural services (i.e. mental wellbeing). As the fields of planning and city design emerged in the 1800s, early designers recognized some of the physical aspects of these urban climate conditions and ecological patterns (Eisenman, 2013; Howard, 1833; Thompson, 2011).

The urban climate also plays a significant role in the services and disservices of urban infrastructure. Recently, the United Nations and World Meteorological Organization have created a framework that integrates urban ecosystem services and urban climate services into Integrated Urban Services (IUS) (Baklanov et al., 2020). This framework explores the relationship between the urban climate and the urban infrastructure by using case studies from Hong Kong, Paris, Toronto, and Mexico City. To examine urban climate's role in IUS, some baseline concepts in urban climate should be defined.

Urban climate is the study of the regional, meso-, and micro-scale climate dynamics that are peculiar to cities (Oke et al., 2017). Cities create unique surface to boundary-layer meteorological patterns that modify the regional climate through the intervention of human development. The implementation of road surfaces, buildings (and associated heating, ventilation, and air conditioning systems), vehicles and other forms of transportation, as well as the concentration of people produces a local atmosphere that traps heat within the city (often considered an ecosystem disservice, particularly in the warm season), slowing the natural nocturnal cooling cycles of the region (Oke et al., 2017). The built environment absorbs shortwave radiation and directly converts this energy to heat rather than using this energy in processes such as evapotranspiration. In addition to the heat-trapping effect of the built environment on climate relative to natural materials, the built environment also modifies the radiative energy balance of the area (another ecosystem disservice in the warm season). The built environment modifies the amount of radiation that is reflected back into the atmosphere as the albedo (radiative reflectance) and the emissivity (radiative absorption) of the material changes.

The typology of the built environment defines the effect of the urban form on urban climate. Stewart and Oke (2012) developed a typology similar to the Land Use Land Cover (LULC) categorization for urban climate. Stewart and Oke's Local Climate Zone (LCZ) classification system uses building height, urban street canyon width/height, building use, and vegetation density, size, and type to create a classification scheme of the urban form. The ten built environment categories and six land cover categories of the LCZ classification (Fig. 1) result in specifications for Sky View Factor (amount of sky visible from a point), building cover fraction, vegetative cover fraction, and impervious cover fraction. These parameters can then be used to assess the urban climate of the LCZ.

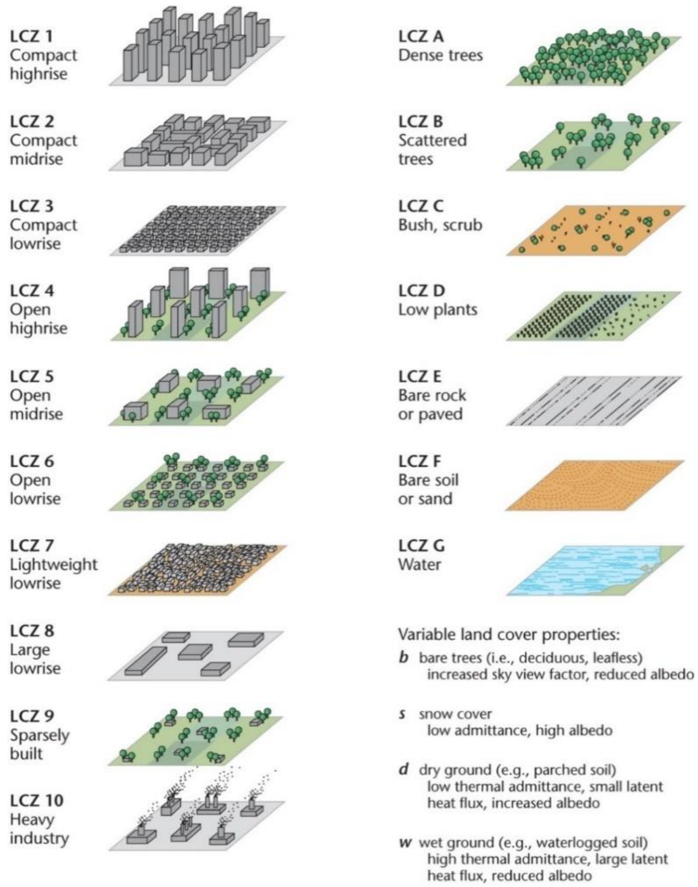

Figure 1 *– The Local Climate Zones from Oke et al., 2017, Urban Climates, © Cambridge University Press 2017.*

The LCZ helps to define the thermal environment of the urban form. Key variables to the thermal environment are surface temperature, air temperature, radiation (often measured by mean radiant temperature). Surface temperature is driven by the surface material characteristics (albedo and emissivity) and the amount of shortwave radiation reaching the surface. These surfaces then re-radiate heat, warming the air. Ambient air temperature is a metric for measuring the internal energy of the atmosphere at a given location relative to the specific heat (American Meteorological Society, 2020). It is the most commonly recognized and reported measure of our thermal environment through hourly weather reporting.

Mean Radiant Temperature (T_{MRT}) is defined as 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure' (ASHRAE, 2001). This definition was established for indoor environments before being adapted for outdoor use (Guo et al., 2020; Nikolopoulou et al., 2001; Spagnolo and de Dear, 2003; Thorsson et al., 2007). T_{MRT} incorporates the radiative load (direct and reflected shortwave radiation) on a point or volume and the thermal energy of the atmosphere to define the environmental heat stressors on a body. This is modified by the air flow and presence of water vapor in the atmosphere. T_{MRT} represents the environmental terms of thermal comfort and depicts the difference in thermal exposure between unshaded, shaded by passive cooling, and shaded by vegetation.

Thermal comfort incorporates the physiological and psychological conditions of an individual that define levels of comfort/discomfort in the environment. The "condition of mind" defines perceived thermal comfort and is the internationally accepted understanding of how thermal comfort is assessed (ISO, 2005). While individual human perception is important, this is subjective and easier to collect for individuals. However, as a measure, thermal comfort is difficult to define for a population interacting with the urban environment. Due to this subjectivity, many scientists focus on the environmental influences on the radiative load as a measure of thermal exposure (which summarizes the physical conditions that are considered alongside subjective perception to create thermal comfort) to examine the means by which urban design can provide a better environment for improving thermal comfort. All of these measures help cities identify hot spots and reduce thermal exposure of residents. Most cities concentrate on two main types of urban heat mitigation strategies. One is to use cooling grey infrastructure (e.g. shade structures or other abiotic structures that provide shade) to mechanically engineer a cooler environment. The other is to utilize green infrastructure (e.g. trees and vegetation) to bioengineer a cooler environment that incorporates more ecosystem services (mitigation of urban air pollutants, evapotranspiration, and nature contact). These cooling grey and green strategies have a long history of improving cities' climate and health.

1.3 Design, Urban Climate, and Mental Health Nexus

From the dawn of industrial cities, design scholars of urban environments have alluded to a connection between design, urban environmental conditions (i.e. urban climate), and human health (physiological and psychological) (Thompson, 2011). This connection is foundational to the practice of city design. In particular, connections between urban design, urban climate, and mental health appear in several prominent designer's calls for parks and green space to address mental health symptoms (specifically schizophrenia) that result from negative urban climate conditions (Eisenman, 2016, 2013; Howard, 1898). These designers made their recommendations for the most part based on anecdotal evidence, observations, personal experience, and unproven theories. Scientific evidence in public health started to inform city design decisions in the 20th Century, such as extreme air pollution events and other public health emergencies. A commonly cited early scientific study is Dr. W.P.D. Logan's work on the Great London Smog event in December 1952, where he attributed 4,000 deaths to the smog (Logan, 1953), but more rigorous and nuanced studies in more recent decades have made broader empirical connections between city design, climate, and health (Jacobs et al., 2018; Polivka, 2018). Yet, even early city designers recognized important urban climate patterns and attempted to address city design around three interrelated factors for health: heat, sunlight exposure, and nature contact.

Heat and Sunlight Exposure (Thermal Comfort)

19th century revolutions in city building also called for revolutions in infrastructure — green infrastructure or nature itself as a building material was a key innovation. As early as the 1830s, cities began to have design ambitions to integrate natural systems and their associated services into cities in more intentional ways to resolve poor environmental quality and improve livability. This ambition led to many city greening intentions with cities such as Chicago adopting a vision of the “Urbs in Horto” or “City in the Garden” as a centralizing pathway of good city design (Klinkhamer, 2016; “Park Districts,” 2005). Early ambitions needed urgency and design champions to take the movement to actual implementation.

First Frederick Law Olmsted (in the United States in the mid-1800s) and later Sir Ebenezer Howard (in England in the early 1900s) became leaders in the parks movement on interspersing green spaces and eco-services within cities of the U.S. and England (Eisenman, 2013; Howard, 1898). Their work was not only focused on the environmental and ecological benefits of re-connecting the natural world, their visions explicitly endeavored to improve the quality of life and wellbeing of city-dwellers through urban ecological design. The town-country magnet of Sir Ebenezer Howard's vision included attractive greening features drawing the city-dweller to this garden city with benefits such as: "No Sweating", "Pure Air and Water", "Good Drainage", "No Smoke", and "Bright Homes and Gardens". While dated in terms of language, Howard’s intended outcomes for his Garden Cities point to some of the underlying issues associated with the urban form. Though less apparent today, Howard’s town-country model addresses those issues through cooling grey and green strategies.

Using empirical research, Figure 2 illustrates the current understanding to support Howard’s 19th century theories of the physiological and psychological impacts of urbanization on the human body for heat (Anderson, 1989; Kuo and Sullivan, 2001; Lewis, 1992; McGregor and Vanos, 2018). Although in the 19th century, design advocates might not have had an explicit awareness of urban climate dynamics, they used observation to build theories of how design impacted urban environments and people. Howard's efforts were focused on improving the urban climate of the city by creating a "garden city" that allowed the city-dweller to experience important health benefits from green infrastructure that were unavailable within the city due to the form of the urban city center. He envisioned life for city-dwellers where cooler air temperatures (no sweating), better ventilation (pure air and water, no smoke), improved sanitation and healthier indoor conditions (good drainage, bright homes and gardens) prevailed. Today, I use design theory that is a hybrid between these early normative hunches and decades of empirical evidence to create grey and green infrastructure that improves these same issues for city-dwellers (Fig. 3).

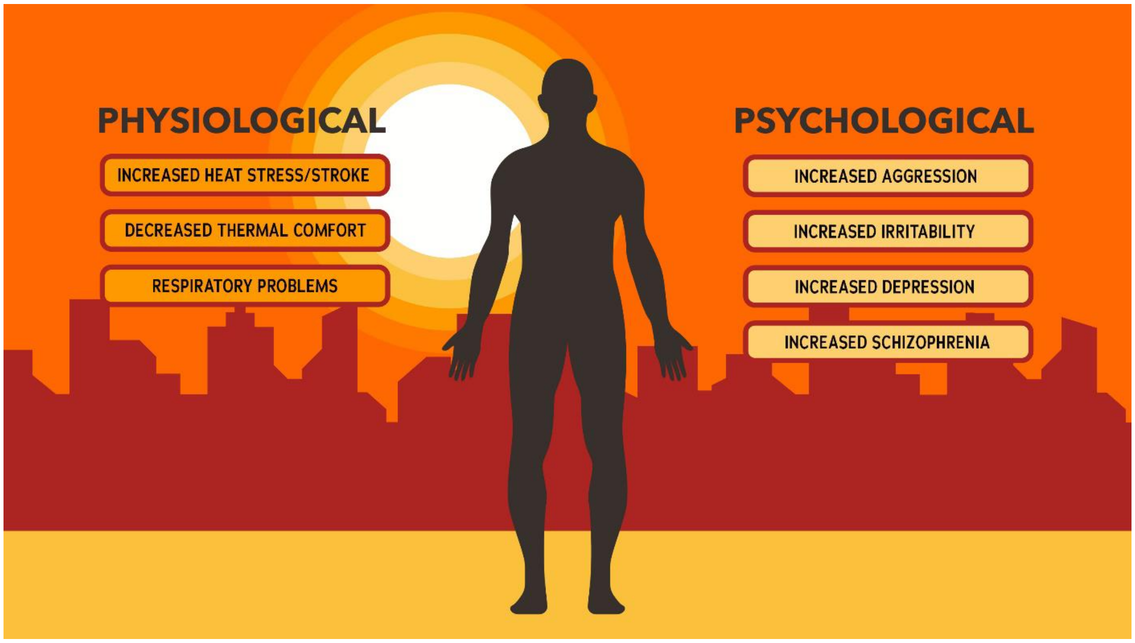

Figure 2 *– The physiological and psychological impacts of the urban environment on the human body for heat.*

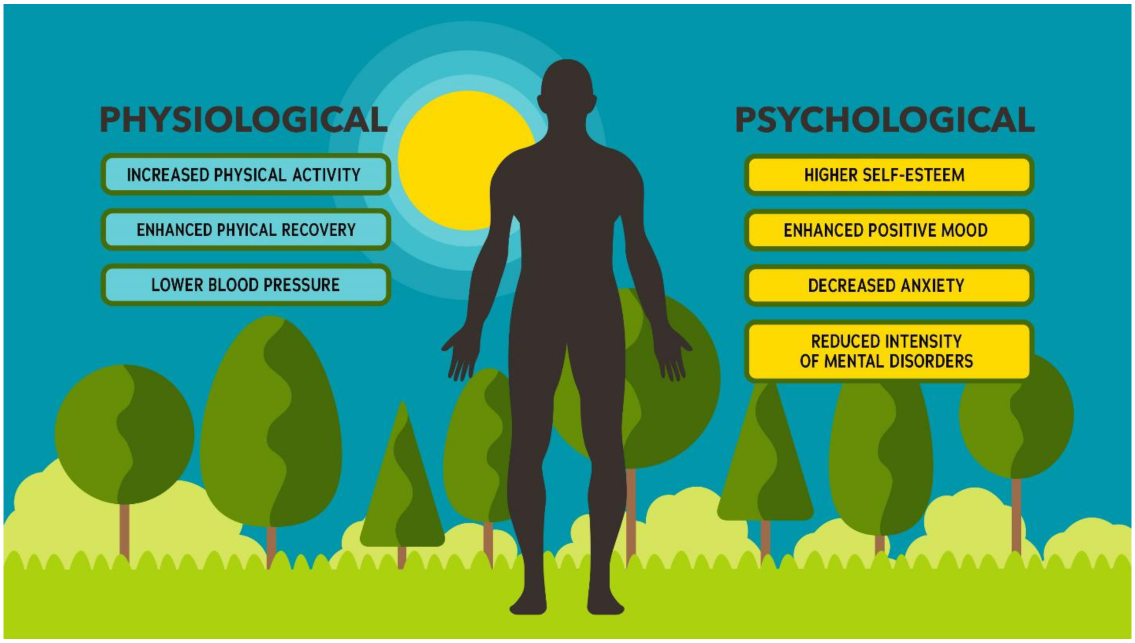

Figure 3 *– The physiological and psychological impacts of nature contact on the human body.*

Nature Contact

Olmsted brought nature to the city and preserved nature in the city in the United States of America. His "Emerald Necklace" in and around Boston, Massachusetts, built in the mid to late 1800s, provided other designers such as Howard with concepts about nature and the benefits to the urban population by having a natural landscape to escape from city life (Eisenman, 2013). Yet, both of these urban designers were not exclusively focused on the physical improvements to the city and health of the city-dweller. There are mental wellbeing concerns woven into the fabric of their arguments and designs. Howard and Olmsted were convinced that increased contact with the natural world improves mental wellbeing, from reducing incidence of depression to alleviating even less understood issues such as schizophrenia and other manic disorders (Berry et al., 2010).

During and since Howard and Olmsted completed their works, research over the past 150 years has indicated that mental wellbeing (including schizophrenia) may be have an increased rate of occurrence in cities. From U.S. 1840 census questions inquiring into the number of "crazy" persons in a household to more modern approaches that statistically analyze differences in schizophrenia based on location of birth (Vassos et al., 2016), there is evidence suggesting a detrimental relationship between the urban infrastructure and the mental wellbeing of the city-dweller. Howard also attempted to address this in his town-country magnet. Howard identified the city features "isolation of crowds", "crowded dwellings" and an assortment of stressful environmental and social factors that he believed an increase in contact with nature could counteract. Many of these design, climate, and health observations were made separately or linked in very simplistic manners. Figure 3 describes current evidence from research that point to the physiological and psychological benefits of nature contact which further support and extend the work of both Howard and Olmsted (Barton and Pretty, 2010; Santamouris et al., 2018; Ulrich, 1984; Ulrich et al., 1991). Although early planners and designers recognized some of the physical aspects of these urban climate and ecological patterns, they also under-examined their social drivers. The interrelationships between design, climate, and health were under-examined due to the complexity involved in teasing apart the relationships of these three interconnected foci. To illustrate our argument, I now go more in depth into the interrelationship between built environment, urban climate, and one mental health disorder -— schizophrenia.

1.4 Discussion

Building Theories for Practice

The evidence for linking exposure to environmental stressors and schizophrenic crises and episodes

Medical and atmospheric research over the past three decades has taken a more nuanced approach to estimating the influence of weather and microclimatic conditions on a variety of personal and community impacts including on mental health. Since city life has been linked to psychosis (Lewis, 1992; March et al., 2008; Vassos et al., 2016), recent research has focused on urban populations and how the ambient air temperature benefits or burdens the local population who suffer from schizophrenic disorders. Hasegewa et al. (2005) found that neurotransmission impairment to the pre-optic anterior hypothalamus results in a breakdown in the thermoregulatory function of the brain. The neuro-psychiatric research has been the foundation for studies in the medical and atmospheric sciences to understand the relationship. Ambient air temperatures above varying thresholds (dependent on location) have been connected to increases in the risk of hospitalization due to schizophrenia; estimates point to upwards of a 1.10 increase in the relative risk of hospitalization for every 1 °C increase in ambient air temperature (Hansen et al., 2008; Kim et al., 2014; Lee et al., 2002; Sung et al., 2011; Trang et al., 2016; Wang et al., 2014). Relative risk describes the impact that an independent variable (such as the environment) has on the health outcome of concern relative to a baseline risk of the health outcome. In this area of research, a relative risk of 1.10 describes a 10% increase in the number of hospitalizations due to schizophrenia for every 1 °C increase in ambient air temperature. Ambient air temperature and internal brain core temperature are both clearly linked to disruptions in thermoregulatory function of the brain in the literature.

Beyond ambient air temperature, research has also shown that for all manic mental health disorders (manic depressive, bipolar, and schizophrenia), the number of hours of daylight and amount of solar radiation received significantly impact the management of these disorders. Unlike individuals with depressive disorders such as Seasonal Affective Disorder (SAD), manic disorder episodes actually increase in frequency and intensity under increased daylight hours and solar radiation (Volpe and Del Porto, 2006). Therefore, for studying the mental wellbeing of a population, there must be concern taken not only for cooling the ambient air temperature, but also for the entire radiation load on the individual. T_{MRT} or a measure combining air temperature, humidity, wind speed, and radiation is a better estimate for the radiation load than just the ambient air temperature. Phoenix, Arizona is an example of a city where this interrelationship between urban design, climate, and mental health may be a particularly important public health issue due to high temperatures and abundant sunlight.

Thermally and Psychologically Inequitable Landscapes

Clearly, Howard and Olmsted thought a key approach to improving urban society's quality of life is through improved atmospheric conditions, but also via increased direct contact with the natural ecological systems that had been (and to some extent, still are) diminished in urban areas. However, their critique was environmentally-deterministic and socially problematic in that they were overly focused on a one-way directed process of the built environment on people, ignoring the interrelated social processes of urban climate production. Today, city officials push to increase use of cooling grey and green mitigation strategies in cities based on these century-long narratives and cooling values backed up by more recent empirical understandings. Yet, in this City government, top-down approach, the design community struggles to prioritize community-informed and culturally contextual design strategies over universal and general physical ones (Hamstead et al., 2020). Recent participatory action heat research (Guardaro et al., 2020) has documented community design processes where the community informed physical strategies were based on bi-lingual workshops led by community leaders. Thus, they were culturally contextual to those neighborhoods and better represented the identity and values of the community. This type of action research is trying to address deficiencies in past heat mitigation processes to address at least three equity issues related to inequitable cooling of cities with implications for climate and health: 1) environmental racism; 2) the inequitable distribution of cooling grey and green infrastructure; and 3) ecological gentrification.

The 19th century greening movement made progress toward more equitable distribution of urban green infrastructure throughout industrial metropolises for some, but not for all. The greening processes by majority Anglo-led governments and nonprofits, particularly in North America, served to entrench legacies of oppression and environmental racism (Agyeman, 2005; Agyeman et al., 2003). Centuries of environmental racism processes have resulted in more vulnerable communities of color as compared to white communities. Even today, these inequities can be reinforced by white dominance in framing of environmental priorities about strategies.

Today, greening efforts are often framed in lack of funding for installation and maintenance of cooling grey or green infrastructure with opposition and conflict between priorities of cooling grey infrastructure and green space, and investment in transportation, utilities, and other grey infrastructure. Power, greed, and other more utilitarian, technological or economically-centered values (e.g. limited tax dollars for maintenance of cool environments) have resulted in limited successes in the implementation of cool grey infrastructure and green space. Yet, these successes in green space interventions have been uneven in their implementation and hide their Anglo-orientation as “normal” or “default” values or mindset (Bolin et al., 2005; Harlan et al., 2006). Taylor (2007) points to a lack of diversity in the staffing of environmental organizations as well as faculty that lead to fewer students of color, which in turn makes it hard to increase the diversity and improve communication and relations with communities of color.

Ultimately, diversity must move from an add-on to a central pillar of the environmental organization for its success. If greening and cooling strategies are not developed with a clear understanding of historical traumas, intentional community representation within and on the design process, and integrating current community needs they may not represent communities of colors' values. Thus, cooling projects can miss the cultural mark, resulting in lack of community ownership, creating socially unsustainable management, or at worst result in further community trauma. Environmental racism results in the inequitable distribution of green infrastructure and its cooling and psychological benefits.

Legacies of environmental injustices have created the current uneven distribution of cooling grey infrastructure and urban forests with their resultant climate regulation services producing more heat-vulnerable households in many mid-sized to large metropolitan areas (Bolin et al., 2005). Heynen et al. (2006) found uneven shade tree distribution in Milwaukee, Wisconsin where Hispanics saw decreased canopy cover compared to the general population. Land surface temperatures have also been found to be higher in lower-income, communities of color (Huang and Cadenasso, 2016). Jenerette et al. (2007) found that low-income Latino neighborhoods in Phoenix, Arizona had higher exposure to high surface temperatures than whiter, wealthier neighborhoods. For every $10,000 increase in income, surface temperatures were 0.28 °C cooler at 10am on a May morning (Jenerette et al., 2007). Thus, many communities of color tend to also be more heat vulnerable than other communities. Reid et al. (2009) define heat vulnerability as a combination of exposure, sensitivity, and adaptive capacity. Yet, I argue that indices of heat vulnerability do not adequately address mental health given their focus on physical health outcomes only indirectly benefits mental health without explicit consideration of mental health. Therefore, not only are people of color more inequitably exposed to high temperatures creating physiological vulnerabilities, but measures cities are increasingly using to identify vulnerable communities are incomplete due to the lack of consideration for psychological impacts on vulnerability from high temperatures.

Local, state, and federal government agencies are creating heat vulnerability indices to prioritize greening and to address these injustices, such as CalEnvironscreen (California), Cook County Social Vulnerability Index (Chicago), Green Infrastructure Spatial Planning (Detroit), and the Environmental Protection Agency (EPA) (CalEPA and OEHHA, 2017; Center for Environmental Assessment, n.d.; "Cook County Social Vulnerability Index (SVI)," n.d.; Meerow and Newell, 2017). Yet, there is growing concern for unintended consequences such as social-ecological processes like ecological gentrification as urban greening continues to be a desirable attribute for cities (Bowler et al., 2010; Dale and Newman, 2009; Kong et al., 2016).

Ecological gentrification is the phenomenon that occurs when increases in green infrastructure and space lead to rising housing costs and displacement of vulnerable households (Dooling, 2009; Wolch et al., 2014). There is a fine line between providing enough eco-services and causing a gentrification of a neighborhood due to the popularity and abundance of green space and eco-services that supplants the local population with wealthier people who want the location for proximity as well as green space. This line is termed, "just green enough" (Wolch et al., 2014). Thus, any improvement of the local climate and design for improving thermal comfort and mental wellbeing has precipitated an increase in land values and subsequently higher rent. These areas are then occupied by wealthier residents and the vulnerable are pushed out as land value (and rental prices) rise through the cycle of gentrification (Ley, 1994; Marcuse, 1985) to locations that have not seen such improvements and thus the cycle continues without improvement for the vulnerable residents. This has become the modern manifestation of ecological gentrification and environmental injustice.

While this dissertation cannot repair these problems, the research accomplished here is designed to show how taking a more holistic approach to neighborhood redesign can shed light on historical practices of environmental racism and elevate the concern of ecological gentrification. By explicitly examining the impacts of a redesign on the public housing districts which are being maintained (and not removed to another location), discussion can move forward on the efficacy of these interventions for the communities that historically have borne the environmental burden of the city.

Will strategies that maximize thermal comfort also reduce the environmental exposure to stressors of schizophrenia crises?

Public health research has supported the notions suggested by Olmsted and Howard that the amount of cooling grey and green infrastructure an individual interacts with will have a significant impact on their mental wellbeing. Essex researchers found across multiple studies that just 5-10 minutes of exercise co-located with green infrastructure has large positive influence on mood and self-esteem across all populations, with the largest improvements found in individuals with mental health concerns (Barton and Pretty, 2010). Public health research has also shown that vegetation and green infrastructure increase physical health of the population (possibly due to increased exercise), and speed up medical procedure recovery times (Frumkin, 2003; Ulrich, 1984).

Taking the body of research on schizophrenia, heat, sunlight exposure, and nature contact to public health as a whole; approaches that use more equitably distributed and culturally representative cooling grey and green infrastructure may improve both thermal comfort and also reduce the public's exposure to mental health stressors such as schizophrenia. A city that provides a unique case study for the intersection of cityscapes, climate, and mental health is Phoenix, Arizona.

Phoenix, a water poor and hot city (Chow et al., 2012; Larson et al., 2013), struggles to plant and manage its urban forest consisting of street and park trees. As an indicator of the growing recognition of the importance of green infrastructure in building a better city, in 2010 Phoenix adopted its first Tree and Shade Master Plan to increase tree canopy from ~12% in 2003 to 25% by 2030 (Phoenix, 2010). However, since Phoenix's resources for maintaining such infrastructure are more limited than many other cities, the location, design, and implementation of such infrastructure could be paired with cooling grey infrastructure that will help facilitate thermal comfort benefits without detracting from the nature contact benefits sought from green infrastructure (Figs. 1.2-1.3). One example of this might be to re-introduce tree canopies to the canals that cut through the city of Phoenix. The canals are an important blue-grey infrastructure, bringing water from the White Mountains and the Colorado River to provide water for agricultural irrigation and park/lawn water demands. The collocation of tree canopies where there already exists both blue infrastructure (canals) and exercise/recreational pathways through the city can provide a minimally invasive strategy that can maximize the population's access to both green and blue exercise.

A schizophrenic heatscape example: Phoenix, where individuals and communities struggle with a mental health crisis
Edison Eastlake

The Edison Eastlake neighborhood (Fig 1.4) is one of the oldest in Phoenix. Over time, Edison Eastlake has developed into a mainly low income (median annual income <$11,000) public housing district (open, low rise neighborhood, LCZ 6) (Stewart and Oke, 2012) of the city through the political ecology process of formal and informal redlining driven by "environmental racism" (Bolin et al., 2005). The neighborhood is racially diverse with a Latino majority, but this diversity is mostly within the government housing or low-income rental housing that dominates the urban form of this neighborhood (home ownership ~16%). Edison Eastlake is also in close proximity to freeway corridors (bounded on the north and east) and the local international airport (~1 mile to the southeast).

The result of these various environmental conditions is a limit to the opportunities afforded to this neighborhood and its residents (Fig. 4). The community is located east of downtown Phoenix (33.45° N, 112.04° W) and is one of the hotter neighborhoods in the city (nighttime surface temperature ~2 °C warmer than the county average). Phoenix as a whole is a hot, arid city often experiencing 100+ days warmer than 38 °C and little annual rainfall (<23 cm/year) (Conservancy, 2019). Summer 2020 (Jun-Aug) was the hottest summer on record at Phoenix Sky Harbor Airport (averaging 96.7 °C) and prospects for further warming due to greenhouse gas forcing is almost certain (Georgescu et al., 2014). Currently, there is some vegetation and green space in the neighborhood, but as designed, it provides relatively little mitigation of the surrounding heat and air pollution sources and is less than the county average of tree cover (5.3% compared to the county's 8.8%). Additionally, the current lack of green infrastructure does not encourage active transit or promote healthier lifestyles in the neighborhood.

The Edison Eastlake neighborhood also has several alarming health concerns as the community experiences more than twice as many heat-related illnesses as the county average and over twenty times as many heat-associated deaths on average as the county (which has the highest of any county in the United States) (Conservancy, 2019). This community also sees a myriad of mental health issues due to its proximity to one of the main behavioral health units among the county’s hospital network. A hospital located in the neighborhood recently closed (November, 2019). Historically, this hospital housed many of the county’s behavioral health patients.

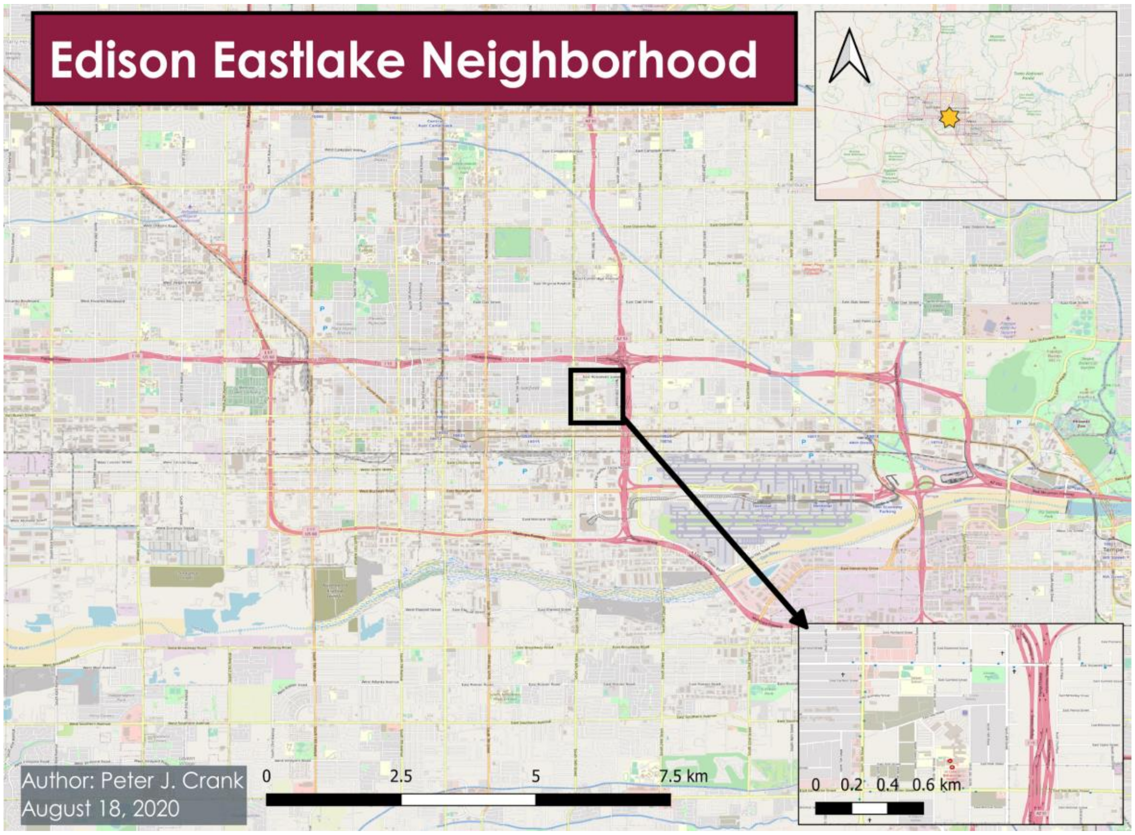

***Figure 4** – Map of the Edison Eastlake relative to the city center of Phoenix.*

How does the built environment help or hurt the schizophrenic population in Phoenix?

In Phoenix, finding ways of inserting even small but well-designed amounts of cooling grey and green infrastructure is vital to the mental wellbeing of the population. This claim is further reinforced by the association of transient populations with schizophrenia. Phoenix draws a large transient population due to the warm winters, little to no rainfall, as well as the regional and national transit connections in the city. This results in a large population of individuals who appear to have a high rate of mental health concerns (including schizophrenia) and are exposed to extreme heat in the city with little to no respite. Implementation of green infrastructure may be more advantageous to the schizophrenic population than cooling grey infrastructure solely due to the dose-response benefits of green infrastructure to mood, self-esteem, physical wellbeing, and recovery times.

Repairing a Thermally Inequitable Landscape

In the case of Phoenix, the impacts of environmental racism and lack of justice in environmental protection for all citizens has been problematic throughout the city's history. Bolin et al., (2005) document the historical and systemic racism of the city, manifested through the treatment of the environment in historically ethnic and low-income neighborhoods. These environmental injustices have created drastic thermal inequities across the city which have been documented by researchers (Harlan et al., 2006). This racism appears most obviously in the form of lack of structural shade and vegetation cover between neighborhoods. The traditionally upper-class, white neighborhoods are lush, well-watered, with buffers placed between the neighborhood and the light, noise, and air pollutants (e.g., factories, industry, shipping, freeways, and the airport). The injustice has taken place as the traditionally ethnic and low-income neighborhoods are forced to have the sources of these pollutants surrounding them, sometimes even having the neighborhood eradicated for the installation of the roadways, airports, and industries.

Our case study in Phoenix is set in one of these neighborhoods. Edison Eastlake was built in the late 1920s and early 1930s as an African-American neighborhood, north of the railroad tracks and between the city of Phoenix and the Salt River. The neighborhood has been encroached upon by the building of the Phoenix Sky Harbor Airport to the southeast and the building of the I-10 interstate, which removed a portion of the neighborhood multiple blocks wide on the north and east corners east of 20th St. and north of Portland and Moreland Streets (Fig. 5). Industry is also on the south and west sides of the neighborhood and extending to the south and west past the downtown portion of the city. Additionally, aside from a mostly open park on the north edge of the neighborhood, the area of the city is mostly without vegetation. Together, these factors reveal the consistent environmental racism and injustice of the city upon this neighborhood and the community that lives there. Yet, the city has begun to move toward rectifying these injustices through guidance by the Nature's Cooling System (NCS), a tri-pronged collaboration between public health departments, community-based organizations, regional NGOs, and academic institutions seeking to ameliorate the thermal inequity of Edison Eastlake.

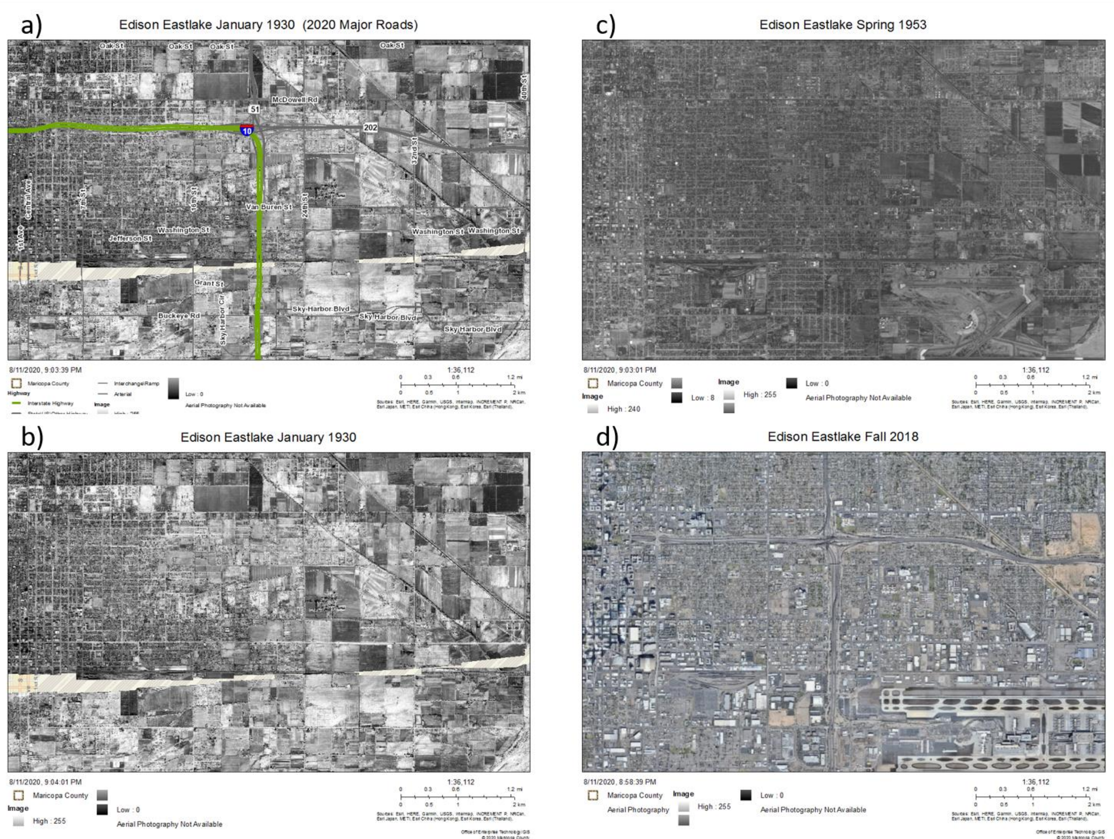

Figure 5 – A four-panel of aerial photographs publicly available via https://gis.maricopa.gov/GIO/HistoricalAerial/index.html. a) Is the aerial photography from 1930 with 2020 major roads overlaid, b-d) depict the urbanization and encroachment of polluting byways and industries on the Edison Eastlake neighborhood.

One timely opportunity to study the impact of urban infrastructure on the surrounding environment in Phoenix is in collaboration with the city in a housing redevelopment project sponsored by the Choice Housing Grant. Choice Neighborhoods is a U.S. Department of Housing and Urban Development (HUD) program to "support locally driven strategies that address struggling neighborhoods with distressed public or HUD-assisted housing through a comprehensive approach to neighborhood transformation" ("Choice Neighborhoods 2016 Implementation Grant Awards," 2016). Due to these harsh thermal and environmental conditions on top of the socio-economic needs of the community, the city chose Edison Eastlake to be the site of a Housing and Urban Development (HUD) Choice Neighborhoods grant (HUD, 2016). The Choice Neighborhoods grant is designed to aid in providing services and amenities to distressed neighborhoods.

The renovation and reconstruction of mixed income housing in central Phoenix is a good location to study best practices for improving the thermal environment of the neighborhood as there is opportunity to consider how changes in building height, vegetative cover, and shade canopies can create contrasting thermal conditions from what currently exists. While the city has their plans in place for reconstruction, a study of the potential impacts on thermal comfort will better inform how the spaces can and will be used upon completion. This will be accomplished through evaluation and validation of numerical modeling of the neighborhood via one of several modeling programs available. Due to the interest in understanding not just air temperature modifications but thermal comfort as a whole, modeling will focus on the output variable of T_{MRT}. The modifications to the design for improving the thermal environment will be tested using the computation fluid dynamic model, ENVI-met, for analysis that includes advection and fluid flow (Bruse and Fleer, 1998). Any modeling scheme of a "real-world" location must have physical measurements to validate the model results. These measurements must also be independent from the input data that forces the boundary conditions of the model (American Society of Mechanical Engineers., 2007; Blocken et al., 2007; Crank et al., 2018).

Discussion of the strengths and weaknesses of different community-informed mitigation strategies in their ability to balance improvements of different goals

The modeling approach will allow for multiple thermal comfort strategies to be tested for their effectiveness. There can be overlap between the two approaches to studying the thermal environment (heat mitigation and thermal comfort); however, common heat mitigation strategies do not include the thermal comfort component of the mitigation strategy. In most cases, heat mitigation strategies focus on ambient air temperature reductions (Los Angeles, 2014; Ng et al., 2012) whereas thermal comfort strategies seek to address all aspects of the thermal radiation load on the pedestrian (e.g., mean radiant temperature, heat index metrics, etc.) (Emmanuel and Fernando, 2007; Johansson et al., 2014). The model will assess the efficacy of both approaches in the same design given that the city of Phoenix is implementing increased green space, high albedo roofing and paving, and shading infrastructure implementation).

The cooling grey infrastructure strategies (shade structures, high albedo roofing, and high albedo paving) are common approaches to cooling the local atmosphere. However, there are questions regarding the relative effectiveness of the strategies for T_{MRT} reductions (Ali-Toudert and Mayer, 2007; Thorsson et al., 2014). Shade structures of various forms have been tested and find them to be effective, but once again there are some concerns as to how effective due to the heat transfer from the bottom side of the shade structure to the surface and from the surface to the bottom side of the shade infrastructure.

Green infrastructure has also been shown to have benefits, though this type of infrastructure also has its own set of limitations and concerns. First, in Phoenix, the use of vegetation is severely limited due to the water limitations of the Sonoran Desert. The native vegetation to the Sonoran Desert does not have large leaf area indices (LAI), which provides more shade and evapotranspiration from solar radiation than vegetation with a small LAI. This restricts the effectiveness of the vegetation to provide critical cooling services. Additionally, there are concerns about the maintenance, pollution, and replacement of green infrastructure. Green infrastructure has also been shown to increase the moisture content of the local atmosphere as well as increasing the number and type of insects and small animals in the neighborhood. Yet, there is a desire to know the relative effectiveness because the additional mental wellbeing benefits of the green infrastructure may recoup the difference in thermal comfort between the cooling grey and green infrastructure.

1.5 Conclusion

Planners and designers are tasked with creating urban landscapes that address the most pressing issues of the community and decision makers with the city. Yet, in an effort to ensure community members and city managers of urban neighborhoods are satisfied, while also attempting to address some of the most apparent environmental concerns in urban areas (i.e., the UHI) the mental health of the community has been largely absent from planning and design documents and projects. Therefore, I seek to reframe the discussion of urban design of landscape through an urban climate lens and also bring mental health and the psychological impacts of the UHI into focus for the field of landscape architecture. Integrating green infrastructure with urban design, hot neighborhoods can become physical and psychological oases, creating garden cities for tomorrow. To contribute to realizing such a vision, the research detailed in this dissertation seeks to determine key, near-surface thermal drivers in the urban energy balance for improving thermal comfort and the subsequent benefits for mental wellness in a hot arid city. The dissertation will involve three core research elements: (1) validation of computer modeling for a hot arid neighborhood; (2) assess the efficacy of the planned redesign for the community's thermal environment; and (3) describe the relationship between schizophrenia and the hot Phoenix climate.

Chapter 2 -- Validation of Neighborhood CFD Simulation of the Thermal Environment in Arid Urban Climates

In Chapter 2, I investigate efficacy and validity of numerical models for estimating the thermal environment of Edison Eastlake. I seek to ascertain how effective ENVI-met (a micro-scale CFD model) is at estimating the thermal environment of a hot arid neighborhood. The thermal environment of the urban fabric is highly variable within a neighborhood. To understand the urban fabric's impact on the thermal environment, numerical modeling can be used to account for these variations. Yet, the model requires in situ observations to ensure the model's validity for estimating the thermal environment. Using five in situ stations, the model performed well, though performance suffered when using mobile observations. RMSE values for fixed weather stations ranged from 0.6 to 1.5 °C for air temperature. ENVI-met did not perform as well at validating other variables. This study highlights the value of rigorous validation and the model's sensitivity to soil moisture. The base case assessed here is found to be valid to then test the impacts of new design configurations on the thermal environment.

Chapter 3 -- Assessing Thermal Exposure Impact of Cooling Grey and Green Infrastructure in Desert Climates

Chapter 3 examines the relative impacts of the city's redesign plans on the thermal environment of Edison Eastlake. In this chapter, I consider what the impact of the city's redevelopment plans on the thermal environment of Edison Eastlake is and seek to assess the value of the designs for future neighborhood planning opportunities. Using the validated model from Chapter 2, I simulated the planned designs for the neighborhood. Results indicate that in such hot and dry conditions as were simulated, the redesign only mildly cools pockets of the neighborhood. The dryness of the soil likely inhibits the green space changes to result in appreciable cooling of the thermal environment.

Chapter 4 -- Mental Health and Heat

In Chapter 4, the mental health effects of heat in Maricopa County are investigated. A circular causal pathway connects schizophrenia and extreme heat: the environment can create circumstances that exacerbate mental health issues, and mental health disorders can lead to increased susceptibility to extreme heat. Given the theoretical relationship between heat and mental health, I seek to measure the association of temperature and schizophrenia hospital admissions in an arid urban climate and quantify the associated public health burden. I collected 80,000+ hospitalization records for schizophrenia from 2006-2014 in Maricopa County, Arizona, USA. Using a distributed lag non-linear model (DLNM), the relative risk of schizophrenia hospital admissions increased with higher ambient air temperatures. Schizophrenia hospital admissions notably increased on days with minimum temperature above 30 °C. I estimated the total fraction of schizophrenia hospital admissions attributable to hot minimum temperature as 2.87% (CI: -2.05-6.85%).

CHAPTER 2

VALIDATION OF NEIGHBORHOOD CFD SIMULATION OF THE THERMAL ENVIRONMENT IN THE ARID URBAN CLIMATE OF PHOENIX, ARIZONA

2.1 Introduction

Urban climate research has addressed how the urban fabric has impacted ambient air temperatures relative to rural surroundings using the urban heat island effect (Oke et al., 2017), and there is clear evidence that urban heat is not uniformly distributed throughout the urban area (Harlan et al., 2006). The differential impact of this urban heat historically has left the majority of the burden on the communities and neighborhoods within the city with the least adaptive capacity and often also with the higher sensitivity and most exposure (Cutter et al., 2003; Harlan et al., 2006). As mentioned in Chapter 1, this burden has been termed "environmental racism" (Bolin et al., 2005), which describes the systemic or historical mechanisms through which the wealthier (and historically whiter) neighborhoods have offloaded environmental polluters and waste heat producers to close proximity to the lower income and ethnically diverse neighborhoods. Additionally, the wealth disparity has also resulted in an inequitable application of shade (Bloch, 2019; Darrel Jenerette et al., 2011; *The Heat Is On: A Trust for Public Land Special Report*, 2002).

These disparities drove the neighborhood selection for the analysis of the thermal environment in Edison Eastlake, which has experienced environmental racism and continues to struggle with the harsh thermal environment. In 2016, the City of Phoenix was awarded a Choice Neighborhoods Grant for the Edison Eastlake neighborhood with redevelopment plans that through the work of other ASU researchers and The Nature Conservancy became community-informed and culturally context design driven (Conservancy, 2019). This planning work with the community has led to design plans that significantly increase tree canopy as well as providing more cooling grey infrastructure across the neighborhood.

Yet, the underlying thermal environment still has not been assessed beyond a study of remotely sensed land surface temperature (Conservancy, 2019), and as such the redevelopment project may or may not accomplish its intended goals. There is a need to understand how these disparities affect thermal exposure within these neighborhoods. Therefore, this chapter examines the intra-neighborhood variability of air temperature and mean radiant temperature (T_{MRT}) using computational fluid dynamic (CFD) modeling and in situ measurement validation. The objective of this research is to determine how effective ENVI-met (a CFD model commonly used for urban applications) is at capturing the intra-neighborhood variability of air temperature and T_{MRT} in an arid urban climate.

2.2 Background

Thermal Comfort and Exposure

Assessing the impact of waste heat on a neighborhood and community has been examined through multiple metrics. In fact, there are myriad ways to assess the atmospheric environment and its impacts on the human body (Epstein and Moran, 2006; Höppe, 1999; McGregor and Vanos, 2018; Nikolopoulou et al., 2001). Yet, a general definition has been adopted in describing thermal comfort. According to the International Organization for Standardization (ISO) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), thermal comfort is defined as "…that condition of mind which expresses satisfaction with the thermal environment." (ASHRAE 55.66, 1966; ISO, 2005). Thermal comfort incorporates not just the physical, environmental surroundings, but also has a psychological component to it, the "condition of mind". Outside of the psychological component, the physical or environmental aspects of thermal comfort include ambient air temperature, moisture content of the air, and wind speed (Epstein and Moran, 2006; Hedquist and Brazel, 2014; Kuras et al., 2015; Salata et al., 2016; Uejio et al., 2011). Outside of the psychological component, the physical or environmental aspects of thermal comfort include ambient air temperature, moisture content of the air, and wind speed. A key component of thermal comfort is also radiation at the point of measurement. This includes solar radiation (shortwave radiation) and reflected/re-emitted radiation from the sun, clouds, buildings, and other surfaces (longwave radiation). This is the thermal exposure of the environment which helps drive thermal comfort.

Approaching the impact of waste heat on a neighborhood and community via thermal exposure allows for the physical environment (including the urban built environment) to be assessed without requiring a consideration for the physiological or psychological components of the individual that define thermal comfort.
Using Mean Radiant Temperature (T_{MRT}) to measure the radiative forcing and load on a human body, the impact of the thermal environment can be assessed for thermal exposure. Equation 2.1 details the calculation of T_{MRT} as implemented in ENVI-met using the methodology of Thorsson et al. (2007). Here, T_{MRT} is defined by the 6-directional radiation flux densities (K_i and L_i) [Wm^{-2}] with the Stefan-Boltzmann constant σ (5.67E-8 $Wm^{-2}K^{-4}$). These radiative fluxes require an absorption coefficient to represent the fraction of radiation absorbed by the human body (exposed skin and clothing). The shortwave coefficient (α_k) is 0.70 and the longwave coefficient (α_l) is 0.97. To calculate T_{MRT} correctly for an adult human, a weighting factor of 0.06 for up/down and 0.22 for cardinal directions is applied (Höppe, 1999; ISO, 1998).

$$T_{MRT} = \left[\sum_{i=1}^{6} \frac{W_i(a_k K_i + a_l L_i)}{a_l \sigma}\right]^{1/4} - 273.15$$

Eq. 2.1

Computational Fluid Dynamic Modeling

CFD modeling has enabled many researchers to examine the relationships of urban design and form with thermal exposure, because CFD models can resolve heat transfer and air flow within a neighborhood. ENVI-met is a non-hydrostatic CFD model that uses Reynolds-Averaged Navier Stokes equation modeling to estimate fluid flow (Bruse and Fleer, 1998; Huttner, 2012). ENVI-met is frequently used in the urban climate field to study the effect urban form has on the atmosphere (Crank et al., 2018; Declet-Barreto et al., 2013; Taleghani et al., 2019, 2016). The model also incorporates the variation in solar radiation based on location as well as time of day and year.

The model is frequently used in the urban climate community and for thermal exposure modeling, but as is the case with any model, is not without assumptions and limitations (Crank et al., 2020; Gál and Kántor, 2020; Middel et al., 2014). Yet, in the attempts to address the thermal exposure with ENVI-met, a key component of other modeling disciplines has been left behind, rigorous validation of the model for the outcome being examined. Crank et al. (2018) and others have advocated for more stringent validation and have shown the validity of such measures when using numerical modeling (American Society of Mechanical Engineers., 2007; Blocken et al., 2007; Crank et al., 2020; Gál and Kántor, 2020). Despite these issues, other CFD modeling software is ill-suited to the size of domains necessary for this kind of work (FLUENT, OpenFOAM), and non-CFD codes are not capable of handling the fluid flow needed to understand the thermal environment (RayMan, Urban Weather Generator, SOLWEIG). A long term approach to research is being applied in this study as this validation effort is working in tandem with long term data collection at the study site which is being redeveloped by the City of Phoenix with thermal exposure in mind ("Choice Neighborhoods 2016 Implementation Grant Awards," 2016).

Data Validation Approaches for Numerical Modeling

The configuration and composition of urban form of the neighborhood can benefit or burden the neighborhood in terms of atmospheric conditions, specifically thermal exposure; therefore, data must be collected from multiple sites within the study area to assess the urban microclimate. Observations are then used to assess the validity of modelling efforts to evaluate impacts of the urban form. There is still uncertainty in how many observations are necessary and where they should be located. Many modeling studies use a single point air temperature measurement for validation(Ali-Toudert, 2005; Mirzaei and Haghighat, 2010). One point in a domain may be able to give generic characteristics of the domain; however, in seeking to understand near-surface temperatures, and their causes, a single point within the domain is insufficient (Crank et al., 2020, 2018; Gál and Kántor, 2020; Maggiotto et al., 2014).

The various urban infrastructure designs provide opportunity for one point in space to be vastly different in its thermal environment from another point 5 meters away due to land cover, vegetation, overhangs, buildings, and building materials. Thus, great uncertainty can develop from a low density of measurement sites within the domain. Not only is the density of measurement important, but siting of the instruments must be well documented, and all anticipated types of siting should be represented. This requires adhering to a standardization of measurement methodology (Johansson et al., 2014; Oke, 2006). In Johansson et al.'s review of methodologies in urban climate studies, they call for a standardization of instrument installation heights and reporting of metadata (2014). When looking at the near surface, air temperature and humidity instruments should be 0.6-1.1 m above the surface and have shielding and ventilation to prevent overestimation of air temperature due to radiation loads. Wind velocity and solar radiation should be of a similar height (without shielding and ventilation). To predict near surface air temperatures accurately, these other variables are necessary to understand how the atmosphere is adding, absorbing, or releasing all forms of energy. Validating the model's performance on these variables at standardized heights and station designs greatly informs any discrepancy between modeled and observed near surface air temperatures.

Other research has pointed to significant limitations with using ENVI-met to model micro-climate thermal environments (Crank et al., 2020; Gál and Kántor, 2020). This is due to significant issues with estimate of surface temperature (Park, 2011), heat transfer processes from surfaces to the atmosphere (Maggiotto et al., 2014), and the high solar radiation combined with low humidity and soil moisture in hot arid climates (Crank et al., 2020). Other limitations are associated with the parameterization of the urban form in ENVI-met. To model shade accurately, the model must have a fine-scale resolution to be able to accurately model the existence, size, and thermal properties of overhangs, breezeways, shade sails, and tree canopy (Crank et al., 2020; Crewe et al., 2016; Middel et al., 2014). Each of these presents its own challenges to the model's ability to predict the variation in the thermal environment.

2.3 Methods

Site

As previously mentioned, the City of Phoenix was awarded a $30M Choice Neighborhoods Grant to redevelop the Edison Eastlake neighborhood into mixed-income neighborhoods linking housing improvements with appropriate services, schools, public assets, transportation, and access to jobs in 2016 (HUD, 2016, pp. 6–7). Choice Neighborhoods are a U.S. Department of Housing and Urban Development

(HUD) program to “support locally driven strategies that address struggling neighborhoods with distressed public or HUD-assisted housing through a comprehensive approach to neighborhood transformation” (“Housing Choice Neighborhoods Planning and Action Grant,” 2020). Through the Urban Climate Research Center (UCRC) connection with the Urban Resilience to Extremes Sustainability Research Network (UREx SRN) at Arizona State University, researchers have developed a partnership with the City of Phoenix to aid in the redevelopment of the neighborhood.

The City of Phoenix chose the Edison Eastlake neighborhood as the neighborhood which they would redevelop with their HUD Choice Neighborhoods grant. The Edison Eastlake neighborhood is situated east of downtown Phoenix, just northwest of Sky Harbor International Airport (Fig. 6). The neighborhood is bounded to the north and east by the I-10 freeway. The neighborhood is bounded on the west by St. Luke’s Medical Center, though part of the neighborhood does lie to the south of the medical center. An elementary school that serves the community is located just north of the medical center. To the south of the neighborhood is a key public transit node opportunity. The Valley Metro Light Rail runs to the south of the neighborhood. The housing stock of the neighborhood consists of 1-2 story buildings and is of the LCZ 6 (open low rise).

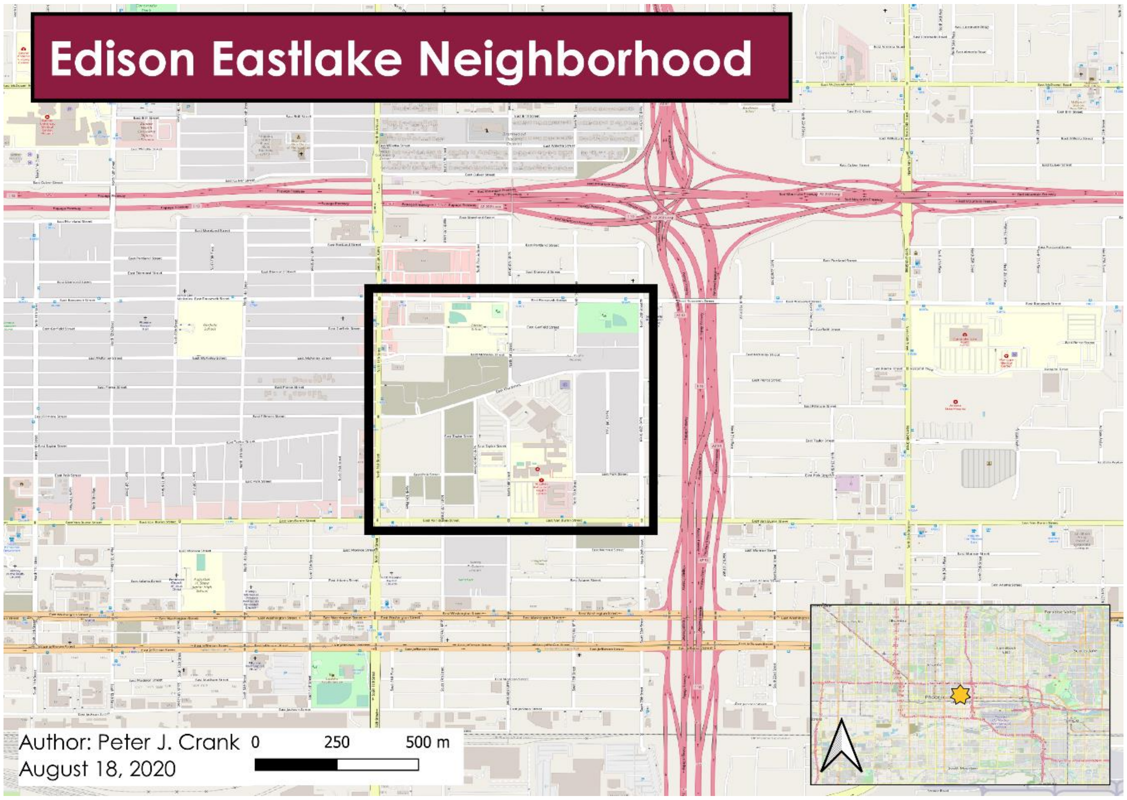

Figure 6 *– Map of Edison Eastlake with the city and airport within the map domain.*

Data Collection

A long-term measurement campaign was initiated during the summer of 2018 (prior to most of the new construction and renovation in the neighborhood) as a collaboration between the UCRC at Arizona State University (ASU), The Nature Conservancy of Arizona (TNC), and the City of Phoenix Housing Department. This campaign will continue until after construction is complete to enable analysis across multiple facets of the neighborhood development (an anticipated 4-6 years). Appendix A notes the specifications of the multiple permanent weather stations deployed in the neighborhood, collecting air temperature, relative humidity, incoming solar radiation, wind speed and direction data. Beyond the fixed weather stations, seasonal field measurement campaigns using MaRTy (Middel and Krayenhoff, 2019) and vehicle traverses will provide more detailed examination of the variations in solar radiation received throughout the neighborhood.

Within the bounds of the neighborhood, I used two fixed weather stations on top of city housing units to collect general weather conditions for the neighborhood. The data were collected every 5 minutes and accessed through an online dashboard. The weather station used HOBO Onset meteorological instruments to collect solar radiation, ambient air temperature, relative humidity, wind speed, and wind direction. These stations were set up to be 2 m above the roof surface and as far as physically possible from air conditioning units. Additionally, 4 temperature and relative humidity sensors were placed in other parts of the neighborhood on electrical poles. These were placed at a height of 3 m to minimize vandalism (Fig. 7). Appendix A denotes the specifications of the data collection instrumentation.

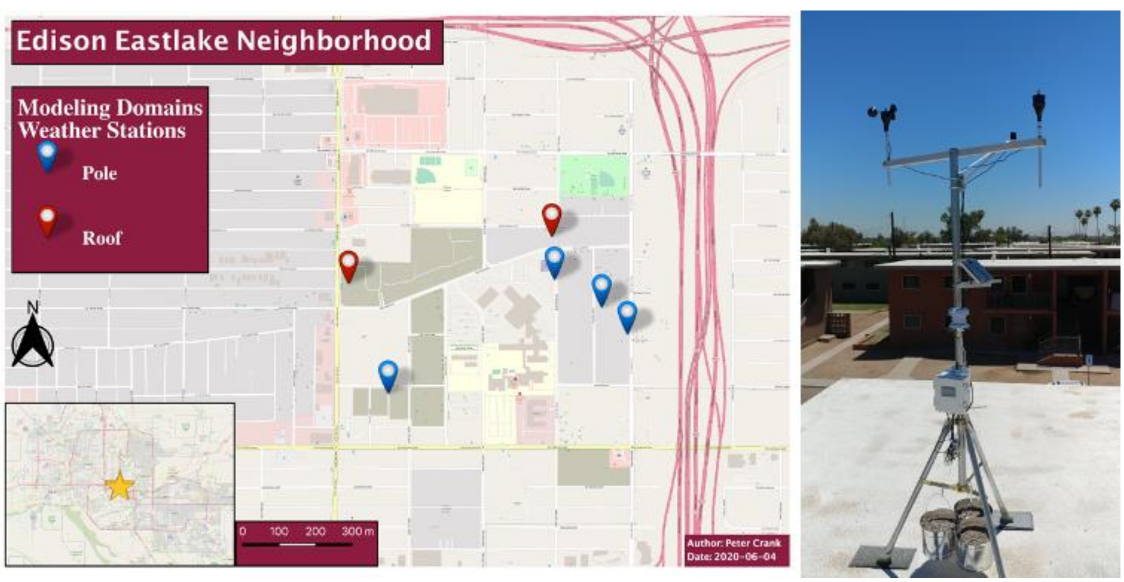

Figure 7 *– Map of the weather stations plus an image of one rooftop and one pole-mounted weather station.*

In addition to fixed weather stations, measurement traverses were conducted in June and October of 2018 and June 2019. These traverses collected data on all of the atmospheric parameters defining a pedestrian's thermal exposure using the MaRTy cart (Middel and Krayenhoff, 2019) and temperature with car-based traverses to aid in minimizing temporal trends in air temperature during the traverse of the neighborhood (Fig. 8). Using the cart thermal exposure data, combined with surface temperatures from above, and the incoming solar radiation from fixed weather stations the data is used to improve the understanding of the atmospheric environment of the neighborhood, examine the thermal exposure implications for pedestrians and residents, and most importantly for modeling purposes, validate data produced by numerical modeling of the neighborhood.

Figure 8 *– Map of the route traverse with traverse instruments. A) shows the route for the traverses, b) is the car traverse thermocouple, and c) shows the two MaRTy carts, as developed by Ariane Middel. The traverses in this neighborhood only used one of the two carts.*

All data went through a data cleaning process in R (version 3.5.1). Using RStudio Version 1.3.959, the data were cleaned up to match units of measurement, location, time of measurement, and time zone. In order to make reasonable estimates of numerical model output to traverse observational data, the traverse measurements must be time de-trended to remove the change in temperature due to the amount of time taken to complete the traverse. Once data are collected, the traverse data are then cropped to 15 minutes before and after the top of the hour and then compared to the numerical model output data for analysis.

Numerical Modeling

There are a variety of numerical models that can be used to answer these questions. However, when restricting to models that can provide the output data necessary to evaluate rigorous metrics of thermal exposure, such as T_{MRT} there are fewer to choose from. Therefore, the baseline microclimate will be evaluated using ENVI-met. In order to evaluate thermal exposure, a numerical model specializing in accurate representation of solar radiation environments may provide a better estimate of MRT in the urban canyon. The ENVI-met model uses weather input to recreate a study period within the model (Table 1). To accomplish this, the nearby (~1 mile) Phoenix Sky Harbor

International Airport weather station data was obtained to force the model (Fig. 9).

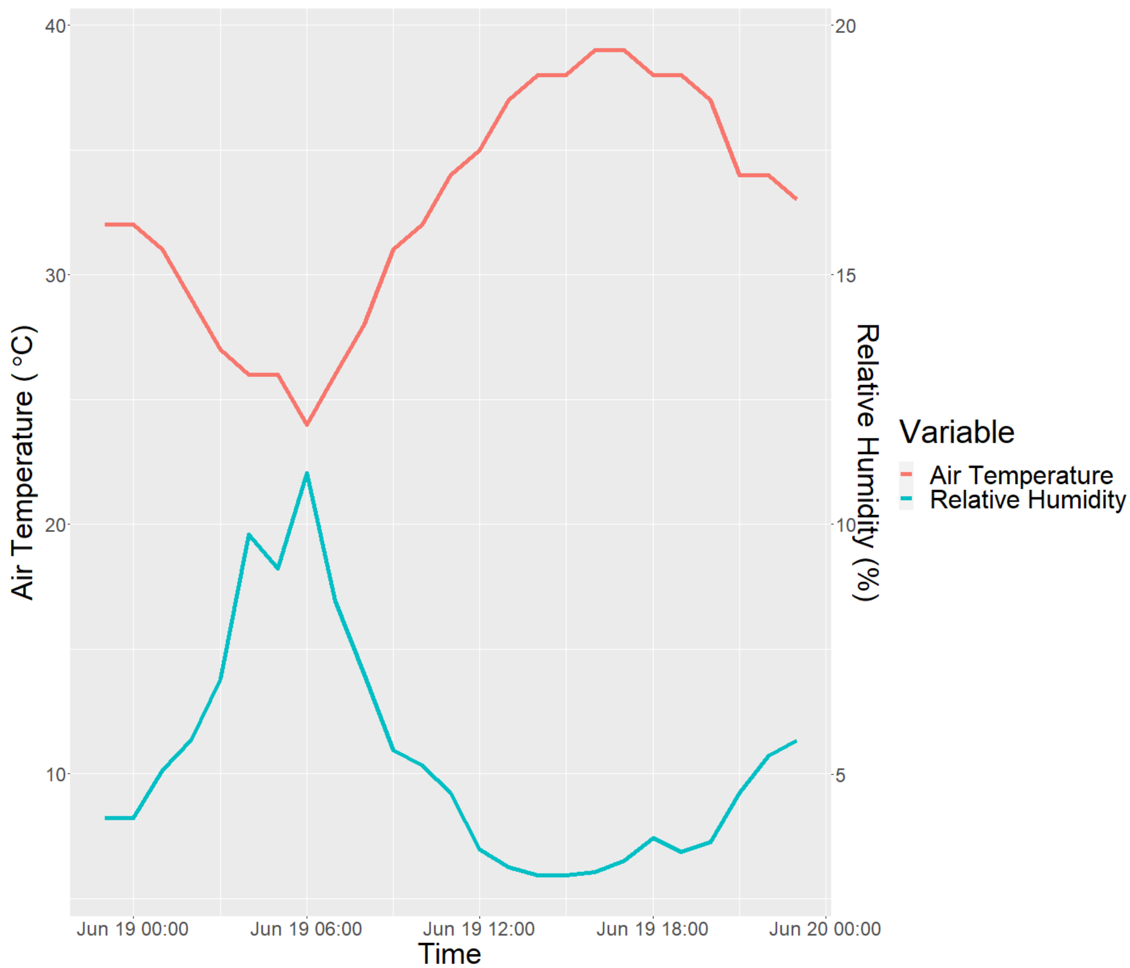

Figure 9 *– Diurnal plot of air temperature and relative humidity used to drive the ENVI-met simulation The data are from Sky Harbor International Airport from June 19, 2019.*

The airport site is not identical to the community, but is representative of the general urban climate of the City and is away from one of the waste heat sources that can influence the neighborhood's microclimate. The ENVI-met domain of the built environment is created using LiDAR data and Google Earth imagery to recreate the buildings, surfaces, and vegetation in the model. The buildings and vegetation were imported through ENVI-met Monde (v. 4.4.4), and the surface characteristics were established using ENVI-met Spaces (v. 4.4.4) (Fig. 10). The baseline case domain is covered by 49.3% impervious surfaces (asphalt and concrete), 14.8% buildings, and

13.8% vegetative cover (grass and trees). The rest of the domain is bare soils comprised of sand or loamy soil.

***Table 1** – ENVI-met input static parameters and settings.*

Start Date Start Time	June 19, 2019 04:00
Simulation duration	18 hours
Wind Speed (m/s)	2.9
Wind Direction (°)	191.0
Simple Forcing	Temperature and Relative Humidity forced using Sky Harbor International Airport weather data
Tree types	Medium crown deciduous tree at 5 m height; Fan palms
Soil Conditions 0-20 cm 20-50 cm 50-200 cm Below 200 cm	 10% RH; 26 °C 15% RH; 26 °C 20% RH; 26 °C 20% RH; 26 °C

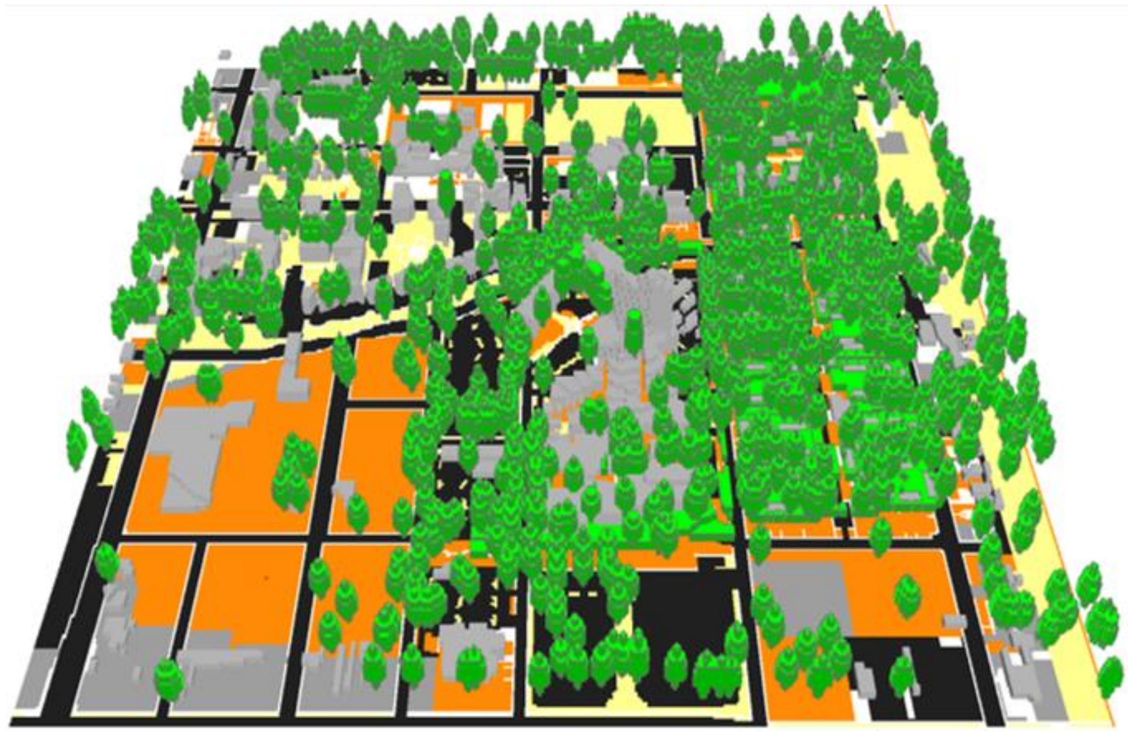

Figure 10 *– A birds-eye view of the ENVI-met domain.*

To evaluate the output of ENVI-met, data collected through stationary weather stations in the neighborhood as well as traverse measurements of air temperature, T_{MRT}, wind, and humidity were used to study the temporal and spatial variation within the ENVI-met domains (Fig. 8). To accomplish this, (1) the output from ENVI-met is exported as a csv for each variable and time of analysis, (2) the output is converted into a grid format using the coordinates of neighborhood; (3) the field measurement data for the same variable (air temperature, humidity (dew point), surface temperature, and mean radiant temperature) and time are then overlaid for analysis spatially. The analysis via sampling the raster data at the points of measurement is completed for each hour of traverse measurement data. This sampling method uses a fuzzy join of the data to allow for error or imprecision in the georeferencing of the data. The join permitted points as far as 1.5 m apart to be joined. The in situ traverse measurements are then compared to the spatially analyzed data from ENVI-met according to (Declet-Barreto et al., 2013).

Additionally, I used the fixed weather stations and collocated with receptor points created within ENVI-met. These points then can be used to analyze the data sub-hourly across the simulation, not just at the specific times of the traverse measurement.

To assess model accuracy, I use four common statistical metrics of quantifying errors as used by Crank et al. (2020) and others (Salata et al., 2016; Zhang et al., 2018) R^2, Mean Bias Error (MBE), Root Mean Square Error in its standard (RMSE), systematic ($RMSE_s$), and unsystematic ($RMSE_u$) formats, and Wilmott's Index of Agreement (*d*), where N is the number of cases, O_i is the observed value, P_i is the predicted (ENVI-met output) value, $\bar{O}$ is the mean of the observed values, $P'_i = P_i - \bar{O}$, and $O'_i = O_i - \bar{O}$. Willmott's *d* is a unitless metric from 0 to 1 where 1 indicates perfect agreement and 0 has no agreement between the data (Willmott, 1981). Acceptable values for Willmott's *d* start at about 0.7 for air temperature and 0.5 for T_{MRT} (Acero and Arrizabalaga, 2018; Crank et al., 2020; Roth and Lim, 2017).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}$$

Eq. 2.2

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)$$

Eq. 2.3

$$\text{RMSE} = \left(\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2\right)^{\frac{1}{2}}$$

Eq. 2.4

$$RMSE_s = \left(\frac{1}{N}\sum_{i=1}^{N}(P'_i - O_i)^2\right)^{\frac{1}{2}}$$

Eq. 2.5

$$RMSE_u = \left(\frac{1}{N}\sum_{i=1}^{N}(P_i - P'_i)^2\right)^{\frac{1}{2}}$$

Eq. 2.6

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P'_i| - |O'_i|)^2}\right]$$

Eq. 2.7

2.4 Results

Descriptive Statistics

Using June 19, 2019 as the forcing data for the ENVI-met model, the day was typical for the summer solstice. Air temperatures were slightly cooler than average, topping out at just under 40 °C for the maximum temperature. No cloud cover was reported for that day, and relative humidity values remained low, peaking at about 6 am with ~12% relative humidity. Winds were light throughout the day, mainly from the south southwest in the morning before switching to a light easterly breeze in the afternoon as the valley breeze in the morning switched to a mountain breeze in the afternoon. Typically, maximum air temperature in the month of June in Phoenix averages at or just above 40 °C with low relative humidity values, low winds, and little to no respite from the sun.

Validation of Air Temperature

The simulation output shows good diurnal agreement between the observational data and the model output (Fig. 11). While two sites (Aeroterra and Luke Krohn) consistently under-estimated air temperature in the late afternoon, the rest of the observations indicate good diurnal agreement between the model and observations. Table 2 details the errors of ENVI-met to observed data as well as the errors from using Sky Harbor Airport data to explain the observed data. A strong correlation exists throughout the model period between the weather input data (Sky Harbor) and the data from fixed sites ($R^2 > 0.89$). ENVI-met performed similarly (and sometimes better) than Sky Harbor in terms of overall agreement (Table 2). The ENVI-met output is best for the three pole-mounted stations with Willmott's Index of Agreement values over 0.96.

ENVI-met performed the most poorly at the Luke Krohn site. Additionally, the RMSE and MBE values for ENVI-met show strong agreement across the sites for observations and modeled output. RMSE values are below 2 °C for all sites and below 1 °C for the pole-mounted weather stations. In many cases, these errors are better than the equivalent errors associated with the data from Sky Harbor.

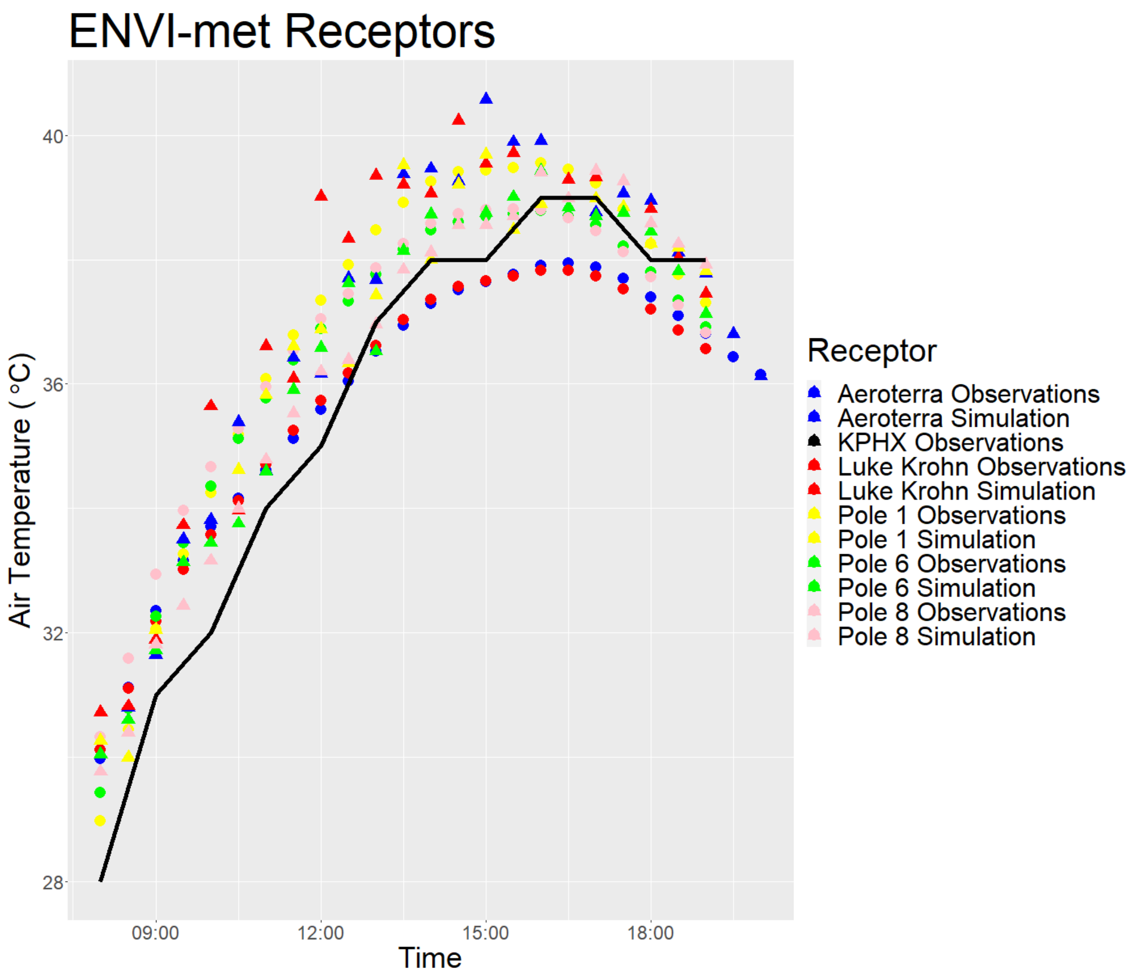

Figure 11 *– Plot of June 19, 2019 temperature data from each fixed validation point, the ENVI-met output, and the data from Sky Harbor used to drive the ENVI-met model.*

Using the traverse measurement data to examine the validity of the ENVI-met model produced dismal results (Table 2). Both car and MaRTy traverse data resulted in Willmott's Index of Agreement less than 0.3. The Willmott's Index of Agreement shows that ENVI-met performing worse at estimating MaRTy data than the car data for the morning and noon traverse. The RMSE for MaRTy data were better or comparable to the car data with the exception of the noon data. Additionally, the car temperature data was more varied than MaRTy with the exception of the noon traverse where they are very similar (Fig. 12).

Table 2 – *Table of air temperature validation metrics for the data. Observations from fixed stations are compared to both ENVI-met and the data used to drive ENVI-met. Observations from traverse measurements are compared to ENVI-met.*

Receptor Air Temperature Validation Metrics

Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
Aeroterra - ENVI-met	0.951	1.388	0.64	1.232	-1.058	0.928
Luke Krohn - ENVI-met	0.945	1.553	0.685	1.393	-1.278	0.917
Pole Station 1 - ENVI-met	0.956	0.691	0.601	0.341	0.271	0.986
Pole Station 6 - ENVI-met	0.959	0.602	0.577	0.174	0.1	0.988
Pole Station 8 - ENVI-met	0.935	0.943	0.749	0.572	0.331	0.968
Aeroterra - KPHX	0.943	1.341	0.769	1.099	-1.049	0.96
Luke Krohn - KPHX	0.854	2.133	1.115	1.818	-1.653	0.895
Pole Station 1 - KPHX	0.958	1.235	0.584	1.088	-0.876	0.962
Pole Station 6 - KPHX	0.96	1.007	0.588	0.818	-0.591	0.975
Pole Station 8 - KPHX	0.99	0.827	0.303	0.769	-0.642	0.984
Car Morning - ENVI-met	0.018	1.828	0.228	0.428	1.755	0.158
MaRTy Morning - ENVI-met	0.014	1.117	0.163	0.428	1.026	0.195
Car Noon - ENVI-met	0.005	2.66	0.689	0.407	2.544	0.289
MaRTy Noon - ENVI-met	0.023	2.204	0.607	0.407	2.096	0.299
Car Afternoon - ENVI-met	0.065	1.16	0.358	0.399	0.987	0.237
MaRTy Afternoon - ENVI-met	0.27	0.434	0.207	0.399	0.266	0.597

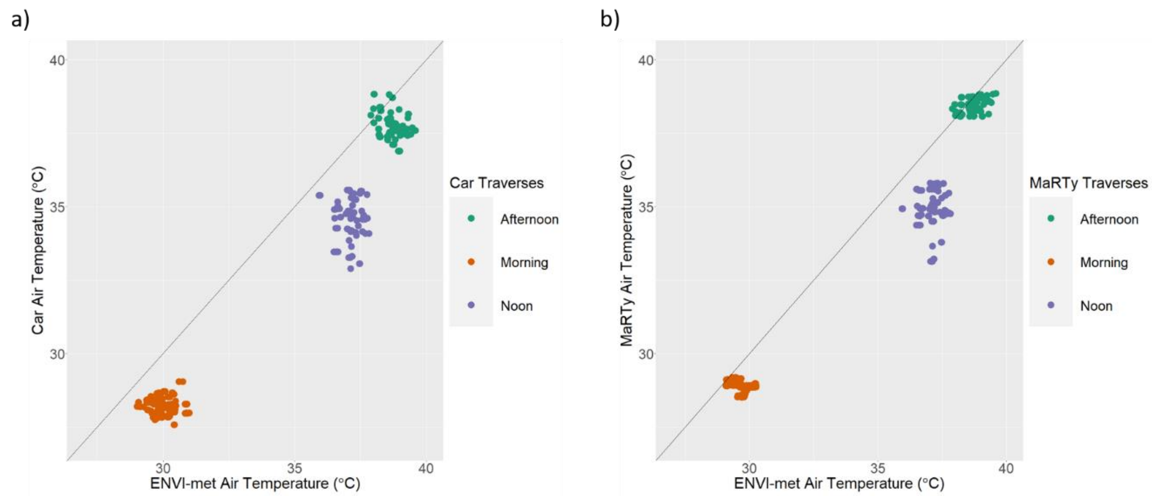

Figure 12 *– Plot of air temperature traverse data and corresponding ENVI-met. Each color delineates a different time of traverse (8 am, 12 pm, 5 pm), a) is the air temperature from the car traverse, and b) is the air temperature from MaRTy.*

Validation of Solar Radiation

When focusing on the validation of solar radiation between ENVI-met and observed data, the points of comparison are restricted to the two rooftop weather stations (Aeroterra and Luke Krohn). Given the limited variation in solar radiation at the top of the urban canopy and the fact that the two sites are on rooftops, the ENVI-met output for the two sites are identical. Sky Harbor Airport also collected solar radiation so validation for the airport data was included. Of note, the airport solar radiation was not used to force the ENVI-met solar radiation output. ENVI-met performed well at modeling the variation in solar radiation over the course of the day (Table 3). R^2 values are around .78 for ENVI-met to Aeroterra (Fig. 13). ENVI-met performed slightly better at the Luke Krohn site ($R^2 = 0.81$) as confirmed by higher agreement between in situ observations and the observations from Sky Harbor ($R^2 = 0.99$).

***Table 3** – Validation metrics and error calculations for Solar Radiation*

Solar Radiation Receptor Validation Metrics

Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
Aeroterra - ENVI-met	0.782	297.695	683.999	308.963	257.535	0.811
Luke Krohn - ENVI-met	0.812	278.82	121.689	176.296	238.929	0.737
Aeroterra - KPHX	0.969	50.161	48.368	282.279	8.583	0.992
Luke Krohn - KPHX	0.994	38.832	22.482	282.279	-30.083	0.995

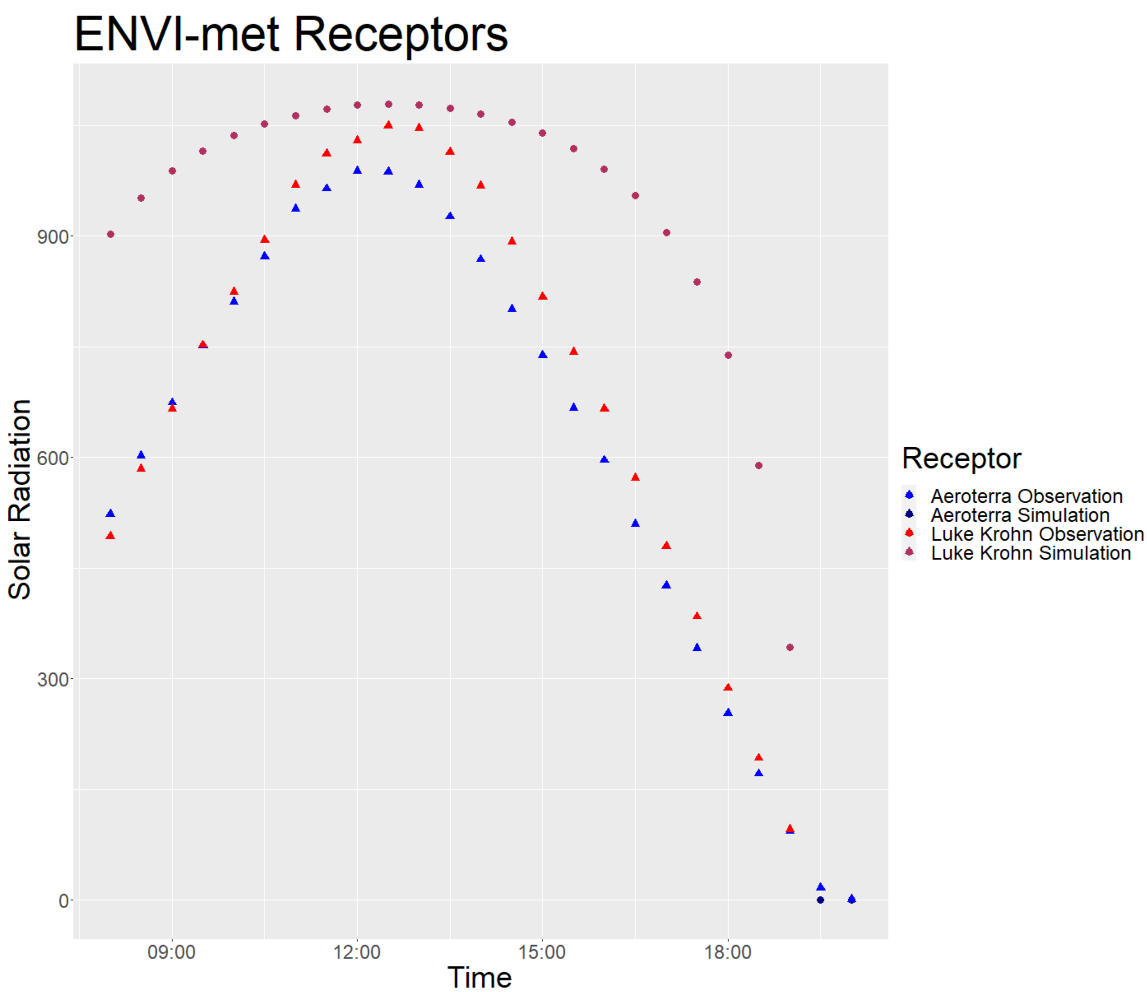

***Figure 13** – Diurnal plot of solar radiation for rooftop weather stations and the ENVI-met output at each point.*

Validation of Relative Humidity

Relative humidity (along with air temperature) are the two variables that were used to hourly force ENVI-met with weather input. The ENVI-met and Sky Harbor data are compared to the fixed stations and to the MaRTy traverse data (Table 4 and Figure 14). The results show moderate success for ENVI-met to predict relative humidity over the domain compared to the airport data. Willmott's Index of Agreement for ENVI-met varies from 0.676 (Pole 6) to 0.808 (Pole 1) with RMSE values below 3%. The MaRTy data resulted in poor explanation of variance (R^2 <0.25) and lower index of agreement values (0.1 – 0.34), but comparable RMSE values.

Table 4 *– Table of relative humidity validation metrics for the data. Observations from fixed stations are compared to both ENVI-met and the data used to drive ENVI-met. Observations from traverse measurements are compared to ENVI-met.*

Relative Humidity Receptor Validation Metrics

Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
Aeroterra - ENVI-met	0.942	2.085	0.463	1.793	-2.031	0.761
Luke Krohn - ENVI-met	0.913	2.259	0.575	1.937	-2.183	0.744
Pole Station 1 - ENVI-met	0.955	2.234	0.388	2.888	-1.907	0.808
Pole Station 6 - ENVI-met	0.887	2.89	0.539	2.795	-2.533	0.676
Pole Station 8 - ENVI-met	0.978	2.963	0.333	2.112	-2.943	0.695
Aeroterra - KPHX	0.961	2.809	0.408	2.449	-2.747	0.721
Luke Krohn - KPHX	0.906	2.93	0.596	2.449	-2.805	0.681
Pole Station 1 - KPHX	0.98	2.446	0.257	2.449	-2.346	0.75
Pole Station 6 - KPHX	0.87	3.52	0.58	2.449	-3.339	0.555
Pole Station 8 - KPHX	0.961	3.47	0.471	2.449	-3.437	0.672
MaRTy Morning - ENVI-met	0	1.64	0.821	1.127	-0.881	0.335
MaRTy Noon - ENVI-met	0.201	2.375	1.796	0.644	-0.165	0.119
MaRTy Afternoon - ENVI-met	0.016	2.756	0.629	0.875	2.508	0.248

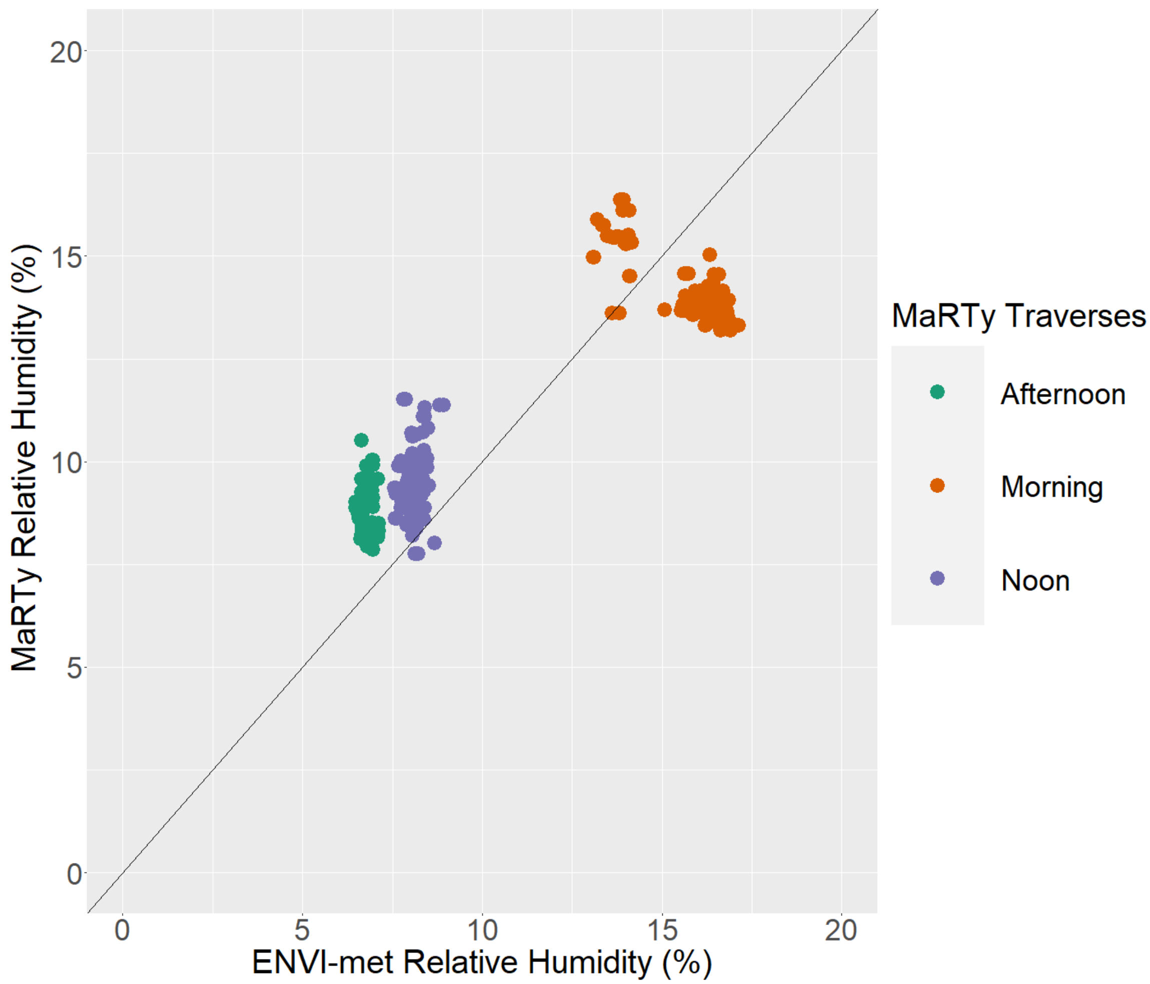

***Figure 14** – Plot of relative humidity traverse data from MaRTy and corresponding ENVI-met. Each color delineates a different time of traverse (8 am, 12 pm, 5 pm).*

Validation of Wind Speed

Using rooftop weather stations and MaRTy data, wind speed values (but not direction) are compared to ENVI-met and Sky Harbor (Table 5). Despite very low agreement with the observational data, ENVI-met resulted in very small MBE and unsystematic RMSE indicative of the model's ability to predict fluid flow through complex geometry. Sky Harbor observations did not match the in situ observational data either but did not perform as well with a higher MBE and unsystematic RMSE. Given our parameterization of ENVI-met did not include an hourly changing wind speed, the results are expected.

Table 5 *– Table of wind speed validation metrics for the data. Observations from fixed stations are compared to both ENVI-met and the data used to drive ENVI-met. Observations from traverse measurements are compared to ENVI-met.*

Wind Speed Receptor Validation Metrics

Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
Aeroterra - ENVI-met	0.07	1.548	0.873	0.017	-1.258	0.444
Luke Krohn - ENVI-met	0.243	1.163	0.591	0.011	0.94	0.431
Aeroterra - KPHX	0.145	1.755	0.921	1.536	0.946	0.571
Luke Krohn - KPHX	0.198	2.09	0.532	1.536	1.571	0.376

Validation of T_{MRT}

The only observations that can be used to derive T_{MRT} are those from the MaRTy data. R^2 values are low (below 0.1) with slight improvement in the index of agreement (0.28-0.38). However, the MBE indicates a systematic *over*-estimation of T_{MRT} by ENVI-met (Table 6). The traverse data show a bit more variability than air temperature. During each of the traverses, there are locations where ENVI-met overestimated and underestimated. Across all three traverses, ENVI-met had no distinct pattern to estimating T_{MRT} (Fig. 15).

Table 6 *– Table of T_{MRT} validation metrics for the data. Observations from fixed stations are compared to both ENVI-met and the data used to drive ENVI-met. Observations from traverse measurements are compared to ENVI-met.*

Mean Radiant Temperature Receptor Validation Metrics

Site	R-Squared	RMSE	RMSEs	RMSEu	MBE	Willmott's Index of Agreement (d)
MaRTy Morning - ENVI-met	0.003	17.783	7.303	1.723	16.127	0.361
MaRTy Noon - ENVI-met	0.098	13.072	4.412	5.508	11.645	0.359
MaRTy Afternoon - ENVI-met	0.01	21.079	5.537	3.052	20.053	0.298

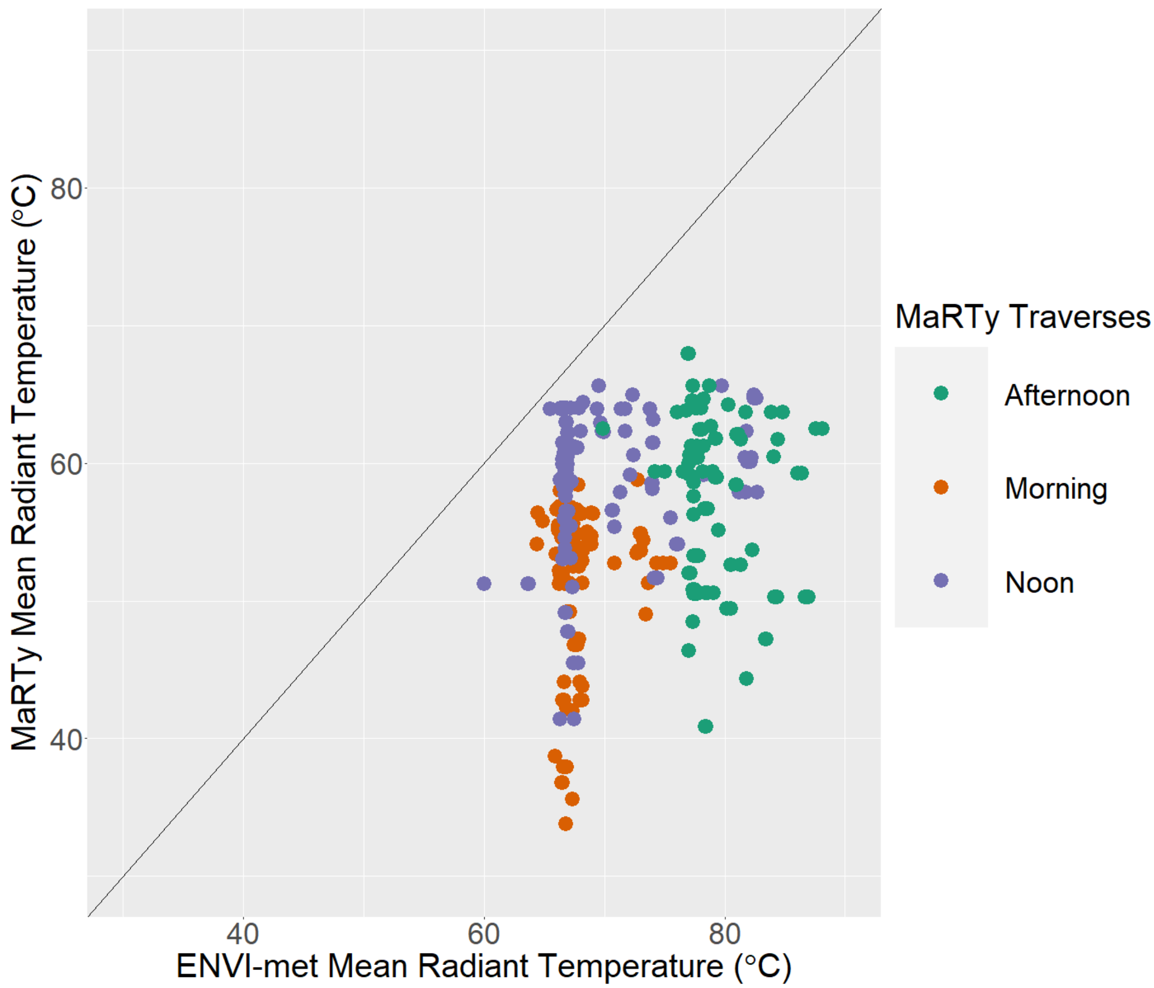

Figure 15 *– Plot of Mean Radiant Temperature traverse data from MaRTy and corresponding ENVI-met. Each color delineates a different time of traverse (8 am, 12 pm, 5 pm).*

2.5 Discussion

ENVI-met modeling results in relatively accurate estimates of the observations for air temperature. Some systematic errors in the model are noticeable and limiting the results of the model (e.g., soil moisture, surface albedo, and wind flow model forcing). These constraints in the model prevent better estimate of the other variables in the model. Regardless, the model's performance shows that ENVI-met can still be used when considering the changes between this baseline and redesign model (Hijmans et al., 2005;

Jandaghian, 2018; Navarro-Racines et al., 2020). Thus, overall, ENVI-met is validated for Edison Eastlake, the data are sufficient to examine differences between sites within the domain. In particular, the model can be used to assess magnitude of the change in the thermal environment due to urban design changes to be made by the city using the delta method (Hawkins et al., 2013; Shick Lee et al., 1992; Wu et al., 2018).

Discussion of Air Temperature

The strong agreement between air temperature in ENVI-met and fixed station observations shows the ability of the model to replicate intra-domain agreement. RMSE values were well within the typical bounds of error (0.8-1.5 °C) compared to commonly reported values between 1.5 and 3 °C in places such as Spain (Acero and Arrizabalaga, 2018), northern Germany (Forouzandeh, 2018), southern Germany (H. Lee et al., 2016), Singapore (Roth and Lim, 2017), and China (Zhang et al., 2018; Zhao and Fong, 2017). Each of these studies found higher RMSE values, but through careful analysis of the errors, some were able to point out the specific issues driving the error and move forward in their analysis from there. Some are less optimistic about the output and the implications for the efficacy of ENVI-met. Yet, the results compared to fixed weather stations were significantly improved.

When looking across the domain, the air temperature data from fixed stations and ENVI-met were closely matched, with the most disagreement coming at the stations sited on top of buildings (Fig. 11). The siting on rooftops was selected for long-term safety, yet is cautioned against (Oke, 2006). As such, this work supports Oke's position as these sites did not result in as good of agreement between model and observations as the pole-mounted weather stations. A key reason posited for the success of the model is the adjustment of soil moisture. Representative soil moisture is key to ensuring that the surfaces do not remain too cool and subsequently dampen the diurnal profile of temperature. Given previously published work that points to issues of ENVI-met not handling extreme heat in arid climates (Crank et al., 2020), it seems reasonable that soil moisture could well be a significant factor in the validation of ENVI-met in hot and arid climates.

There are some reservations with the traverse data and their alignment with ENVI-met. The methodology used was to collect a continuous trek through the neighborhood. As such, the exact spatio-temporal positioning of the traverse data with the model was more challenging and fraught with slight errors as the data had to be joined with a buffer to the ENVI-met model output. This "fuzziness" in spatio-temporal resolution certainly would be a significant limitation in model accuracy. Future work would benefit with taking a different approach to collecting data for the traverse. Another, more successful, approach has been to pre-select sites and mark them with chalk to ensure spatial consistency in data collection sites across time and to allow the instrument to adjust to the location.

Discussion of Solar Radiation

The model output did not align with the observational data (Table 3). The poor results and unique parabolic shape to the diurnal output from ENVI-met suggests that ENVI-met's attempts at depicting the precise location of shading objects is poor. In addition, ENVI-met cannot account for distant urban features that would block low sun-angle radiation. The difference in the parabolic shape led to a significant decrease in agreement between the model and observations (Fig. 13 and Table 3). Few papers have considered in detail the solar radiation as a validation metric. Gál and Kántor (2020) noted that without the forcing of solar radiation data using measured direct solar radiation as well as scattered and diffused solar radiation, the numerical modeling approach will not attain the standard set for by the International Standards

Organization's heat/cold stress requirement, ISO 7726 (ISO, 1998). Using the calculated estimate for solar radiation to force the numerical model increases the likelihood of errors for T_{MRT} within the domain (Weihs et al., 2012). This is likely an outcome of the model design of this research as solar radiation was not forced by observational data. ENVI-met used the day of year, latitude, and longitude to approximate the solar radiation.

Discussion of Relative Humidity

Relative humidity can be a very challenging variable to model, especially in a neighborhood setting such as Edison Eastlake. Individual habits around caring for the lawn and municipal watering schedules can create spikes in relative humidity depending on proximity to a station. The human behavior component to relative humidity is outside the scope of this research but could be an area that might explain some of the decreased model performance. As such, there is little to no validation of relative humidity in the literature, thus it is difficult to determine the success of this model to estimate humidity relative to other studies. As such, the discussion will focus on comparison to observational data. Overall, despite having a fine-scale driver of relative humidity values that are also very localized and not represented in ENVI-met, the model did a fair job of estimating relative humidity. Under new soil conditions, this might improve as the baseline values for soil moisture and evapotranspiration will be more similar (of course still unable to account for the human behavior component to soil wetness) and subsequently create better agreement between the model and observations.

Discussion of Wind Speed

One of the significant limitations to the model parameterization used is the use of constant wind speed and direction. Therefore, the results were unsurprisingly poor. Without the ability to vary the direction of inflow throughout the day, the model will struggle in climates such as Phoenix where there is a significant and prominent valley/mountain breeze that occurs throughout the year (though most apparent in the winter and summer months). Some researchers have studied the wind flow via ENVI-met (Forouzandeh, 2018; Lobaccaro et al., 2018). However, as the basic construction of the model must differ (using the variable wind speed/direction parameterization scheme), the data are not comparable.

Discussion of Mean Radiant Temperature

T_{MRT} has been shown to be a hard variable to estimate with a numerical model as the exact location of the shade is vital to determining mean radiant temperature (Crank et al., 2020). As such, any slight misplacement of a tree or small error in height of tree, building, or shade structure can create problems when comparing to observations. This is likely further hampered by the methodology selected for T_{MRT} observation collection. Using a constantly moving cart rather than selecting points and pausing for longer periods of time (1-2 minutes), the location identified as observation may not perfectly align with the actual location of the observation. As such, the results from ENVI-met output for T_{MRT} are poor.

As Gál and Kántor (2020) pointed out, the overnight longwave upwelling radiation creates significant issues with T_{MRT}. Yet, for this study the night-time conditions are not considered. However, the estimation of surface temperature and the parameterization of heat transfer off of surface materials is another area of concern that several studies have noted (Crank et al., 2020, 2018; Gál and Kántor, 2020; Maggiotto et al., 2014; Park, 2011). This underestimation due to heat transfer and surface temperatures is likely being further exacerbated by the soil condition and surface albedo issues mentioned before in regard to this study. As such, the results are disappointing, yet systematically biased, which permits the careful use of the model output for further analysis.

Limitations

The limitations to this research are split between two main categories: modeling and observational methodology. From a modeling perspective, the standardized solar radiation of ENVI-met and the constant wind speed and direction resulted in limited ability to consider how these two variables are performing relative to the observational data. Future work could apply the new functionality of forcing solar radiation, wind speed, and wind direction to determine whether or not the model is adequately estimating these variables and assess whether or not this would improve the prediction of air or mean radiant temperature as suggested by Gál and Kántor (2020). Soil moisture remains a concern with the model. Despite using measured data from a representative environment (Middel et al., 2014), the uniformity of soil temperature/moisture (spatially and temporally) is not representative to the domain and uncertainties remain as to how much these factors influence the output of the model. Computational time is another limiting factor for the model. The computational demand creates a high computational cost barrier to quickly assess issues in the model and study the impact of small parameterization changes.

The observational methodology also had several shortcomings that limited the use of the data. First, one of the pole-mounted stations disappeared and therefore data was not retrieved. This removed an additional site from which to validate the model. The rooftop weather stations performed poorly relative to the pole-mounted stations. This performance could result from a combination of challenges in ENVI-met to model building heights appropriately and the impact of proximity to solar panels and AC units that are not considered in the model. The rooftop station was also unable to represent the unique climate of urban canyons, which is a concern others have mentioned in general guidance on siting urban weather stations (Oke, 2006). Additionally, the traverses through the domain did not occur rapidly enough to complete the circuit within a 15-minute window before and after the top of the hour. Any data outside of that window was discarded due to time de-trending concerns. Even with a 15-minute window, the change in temperature over that time may still be significant, especially in the morning and evening. Additionally, the circuit methodology may not be the best methodology for validating a numerical model. The constant motion may have resulted in observation points being a few meters off in addition to tall buildings creating GPS inaccuracies greater than the buffer of 1.5 m used to complete the fuzzy join of the traverse data to the ENVI-met data, resulting in errors when comparing to the static cells in ENVI-met.

Another limitation in the observational methodology is the presence of flood irrigation in the park. While no measurements were directly taken in the park, both the car and MaRTy cart passed along the edges of the park. Thus, any residual moisture from flood irrigation may have some effect on measurements at those locations. However, given the general wind flow (particularly in the summer) is from the southwest to the northeast, any cooling provided by the park is likely to be transported out of the neighborhood.

Future lines of research

The validation reveals some small errors remain that could be due to parameterizations. While this dissertation does not consider the effect these parameterization perturbations may have, future work can make small adjustments to soil moisture and surface material albedos in a similar fashion to Jandaghian (2018) and assess the impacts of these adjustments on the change (or delta) in the thermal environment between urban design modifications. Their results showed that for coarser resolution models of the atmosphere these parameterizations and tweaks to the model do not result in statistically significant changes to the output (Jandaghian, 2018). Thus, the model's "delta" between test and control are trustworthy. This delta method is a common procedure for global climate change models, where the errors associated with the model are assumed to be consistent between the baseline and the test case (Hawkins et al., 2013; Hijmans et al., 2005; Navarro-Racines et al., 2020; Shick Lee et al., 1992; Wu et al., 2018). Therefore, future work could modify the parameterization schemes of the model to test what impact these assumptions have on the resulting thermal environment.

Additionally, future work would benefit from a better understanding of the heat transfer associated with extreme (low and high) surface temperatures before re-running the model. Further research would be to run the model under different weather scenarios. Data were collected for October 2019 and can be used to see if the model performs better in a shoulder season where temperatures are not as extreme. Finally, this kind of work is needed with ENVI-met. Without detailed validation of the model, the results are not helpful and potentially misleading. As others have recently noted in their work, ENVI-met is too frequently used indiscriminately and by simply ensuring multiple observational sites are available to validate, the model trustworthiness increases (Crank et al., 2020, 2018; Gál and Kántor, 2020; Maggiotto et al., 2014; Middel et al., 2014).

Future work should continue to build toward a transparent methodology for data collection and analysis to assess ENVI-met's validity in a given environment. This critical approach to validation requires researchers to explicitly test ENVI-met for biases in every new climate and environment. As a model, ENVI-met needs to be "put through its paces" in each new climate regime before moving forward with modeling modifications/outcomes to urban design. Additionally, having more variables to validate can help in improving the model's output and also further diagnose any discrepancies and improve the modeling work in the future.

2.6 Conclusion

The primary goal for this research was to validate and establish a baseline model for the Edison Eastlake neighborhood in Phoenix, AZ using the ENVI-met microscale model. The results of the validation show that the model sufficiently modeled air temperature within the domain. While ENVI-met was not as successful in modeling other variables, the results of this validation analysis provide sufficient evidence that the model can be used to model a neighborhood redesign and compare between designs to assess the effect of urban design modifications. As such, any further analysis of Edison Eastlake using this model as the baseline must be considered with the caveats that: 1) errors within the model are small enough that they will not result in significant changes to the deltas in the thermal environment between this baseline and the redesign test, 2) wind speed and wind direction are static throughout the simulation which is not what is occurring in the observations; and 3) solar radiation values used to force the ENVI-met simulation are not observed, but are made calculated based on the day of year, longitude, and latitude.

CHAPTER 3

ASSESSING THERMAL EXPOSURE IMPACT OF GREEN INFRASTRUCTURE IN DESERT CLIMATES

3.1 Introduction

The need to understand the effect of green and cooling grey infrastructure on the thermal environmentis a key thrust of this study, as the ability to quantify the effects are the means by which this research can be used effectively to inform and influence policies at the local, state, and national levels. Despite the model shortcomings detailed in Chapter 2, this chapter builds on the model by recognizing that the relative impacts of the design changes can be assessed, given the systematic errors of the baseline model (e.g., soil moisture, surface albedo, and wind flow model forcing) using the delta method (Hawkins et al., 2013; Hijmans et al., 2005; Navarro-Racines et al., 2020). As discussed in Chapter 1 and 2, the Edison Eastlake neighborhood is undergoing a redevelopment project funded by the Choice Neighborhoods Grant with HUD and overseen by the City of Phoenix (HUD, 2016).

Improved infrastructure for access to public and active transportation to various parts of the city is also a goal associated with this project. The project uses green space and cooling grey infrastructure to accomplish active transit, physical activity, and community space goals. The design strategies were developed and adapted based on community feedback. The feedback was solicited through bilingual workshops in the community that presented city plans and fostered discussion around designs that better address the needs of the community and envision a future neighborhood that residents want to have.

Given that these designs take on a culturally contextual approach, many of the design elements are intended to address the thermal environment. One of the significant concerns residents had in these workshops was dealing with the extreme heat in Phoenix during summer months (Guardaro et al., 2020, 2019). In workshops, various design elements that can be used to improve conditions for pedestrians in the neighborhood were prominent. While some were focused on social programs to serve the community (such as cooling centers within the neighborhood), many were focused on providing cooling grey and green infrastructure for the neighborhood. This chapter presents numerical modeling of the redevelopment plans for Edison Eastlake and assesses the efficacy of the redevelopment's urban heat mitigation plans for improving the thermal environment of Edison Eastlake.

There are two main approaches to urban heat mitigation. One is to use grey infrastructure to create shade or reflect more radiation out of the urban environment. The other is to re-introduce green infrastructure to create shade, reflect radiation, increase evapotranspiration, and repurpose solar radiation (photosynthesis). These two components of urban heat mitigation are prominent in the Edison Eastlake redesign. Figure 16 shows the architectural renderings of the neighborhood alongside the ENVI-met model to the neighborhood. In these redesigns, the Edison Park in the north of the neighborhood is expanded south, a green corridor connects Edison Park south to the major arterial road, Van Buren St, and the mass transit options along that road (which are also undergoing redevelopment to make the public transit options more visually appealing and cooler). In addition to these introductions of green space and infrastructure, cooling grey infrastructure (mostly in the form of ramadas and shade structures) is also being introduced throughout the neighborhood.

In addition to improvements to outdoor communal spaces, the housing units themselves are being redeveloped. Many of the units were built in the early 1950s (Fig. 16), and not energy efficient or effective at keeping residents cool. The redevelopment plans modernize the housing units and make the area denser, which can be a means of increasing the efficiency of the HVAC systems. While this can also lead to issues of dense urban poverty (Hirsch, 1985), the City introduces mixed income housing options with this redevelopment, seeking to attract a mixture of in-government housing, low- and middle-income residents to be co-located, and foster a community of active transit users. The housing units also will be built with light-colored roofing and some solar panels to reduce energy usage of the neighborhood.

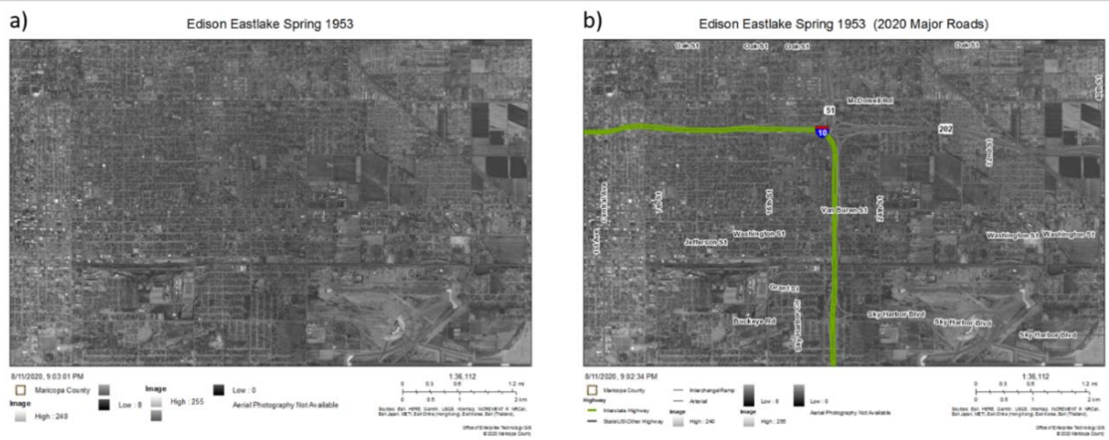

Figure 16 *– Edison Eastlake neighborhood Spring 1953 after Edison Eastlake had been built with (a) its residential layout, and (b) with 2020 major roads added on top.*

Many of the City's efforts to mitigate urban heat are focused on the non-human impacts of heat, yet residents are also concerned about the impacts of the built environment on their experiences of the thermal environment. This plan for redevelopment creates a natural case study in the impacts of these redevelopments that incorporate urban heat mitigation strategies on thermal exposure for residents.

Additionally, this redevelopment provides an excellent opportunity to study how neighborhood redevelopment might benefit or burden the residents in terms of thermal exposure and equity. The redevelopment also provides opportunity to examine how the history of environmental racism, as was discussed in Chapter 1, is being addressed by the City.

Examining the redevelopment impacts on the thermal environment is essential to considering how the City's efforts to use a community-informed, cultural context design strategy will address the history of environmental racism and the ongoing discussion of equity, specifically thermal equity in this case. Thus, while the City is focusing their redevelopment efforts on aesthetics, neighborhood improvements, and the direct cost of redevelopment, the residents are concerned about the safety and shade for the neighborhood. These competing interests are being addressed by the City by creating the green corridor mitigation strategy that is intended to minimize thermal exposure in the neighborhood as well as improve the thermal equity between this neighborhood and other parts of the City of Phoenix.

3.2 Background

The topic of urban heat mitigation strategies, specifically the use of green infrastructure to accomplish this, has been a point of interest internationally for decades (Bowler et al., 2010; Lyle, 1996; Ng et al., 2012; Santamouris, 2014; Santamouris et al., 2018). Much of the research in green space as an urban heat mitigation strategy shows the intervention as effective for cooling the immediate vicinity (0-1km) on the order of 1-2 °C (Bowler et al., 2010). Santamouris et al., (2018) point out the many co-benefits of green infrastructure for urban heat mitigation. These co-benefits include improvement in some aspects of air quality, reduction in waste heat or energy usage by buildings, and non-thermal health benefits (both physical and mental) that can improve the living conditions of the neighborhood or community in which the strategy is implemented. While there are concerns and drawbacks to the use of green space to address some of these co-benefits in Phoenix (such as water needs, slowed overnight cooling, etc.), nevertheless, these strategies have been found to be effective at the local scale, with some indication that they may also help combat the effects of global climate change and the regional effects of the urban heat island (Georgescu et al., 2014).

Cooling grey infrastructure provides many of the thermal benefits of green infrastructure. However, it typically does not produce the same co-benefits and also does not create concerns over water use. Cooling grey infrastructure typically takes the form of shade structures along paths and travel routes. Awnings for buildings and changes in elevated surface albedo are other mechanisms for grey infrastructure to produce cooling benefits. Often, solar panel shade structures are included in this category and while there is some evidence of the benefits during the peak heating hours (Georgescu et al., 2014; Middel et al., 2016), there are also concerns of the effect solar shading has on building energy usage and the nocturnal canopy layer urban heat island effect (Pham et al., 2019).

Beyond the pure, physical meteorological environment, this research is concerned with the impacts of the atmosphere on human thermal comfort. Several researchers define study-specific neutral temperature as a mechanism to determine a population-level definition of thermal comfort, despite being dependent on the "condition of mind" (Lin, 2009; Nikolopoulou et al., 2001). radiant temperature. The beneficial changes in human thermal comfort associated with parks can be extended into neighborhoods through urban planning and design (Chen and Wong, 2006; Chow and Brazel, 2012; H. Lee et al., 2016; Loughner et al., 2012; Ng et al., 2012; Srivanit and Hokao, 2013). Yet, in a review of outdoor thermal comfort studies, Chen and Ng (2012) noted that there are atmospheric issues as well was subjective individual issues to control for and answer when working in thermal comfort research.

There is increasing interest and awareness in the personal and psychological factors of thermal comfort. Understanding how individuals experience thermal variations and their comfort levels in thermal environments has been a focal point of research for some in the field (Middel et al., 2016; Nikolopoulou and Lykoudis, 2006). These factors are often associated with the cognitive relationship between the individual and the space. The personal use of the space is fundamental to how thermal comfort within the space is perceived. Someone who does not want to be in the space will tend to be more thermally uncomfortable (Lin, 2009; Nikolopoulou et al., 2001). These personal factors can also include personal choice in attire which can mitigate or exacerbate thermally uncomfortable conditions (Fanger and others, 1970; Lin, 2009; Middel et al., 2016; Nikolopoulou and Lykoudis, 2006). Yet even beyond these personal influences, the psychological component of human behavior also plays a key role in thermal comfort.

A review of green infrastructure literature by Tzoulas et al. (2007) also indicates that green infrastructure provides ecosystem services that benefit not on the physiological side of human health, but other research points to the psychological as well (Barton and Pretty, 2010; Frumkin, 2003; Santamouris et al., 2018). Looking at Howard's outcomes for physiological wellbeing (Howard, 1898), health and atmospheric data confirm several of these ideas (e.g., cooler air temperatures, improved air quality, better mood) (Barton and Pretty, 2010; Frumkin, 2003; Ulrich, 1984; Ulrich et al., 1991). Research supports his claim that urban life is detriment to the mental wellbeing of people (Bowler et al., 2010; Frumkin, 2003; Kuo and Sullivan, 2001; Lewis, 1992; Maller et al., 2006; March et al., 2008; Taylor et al., 2001). The urban climate has multi-faceted impacts on all components of human society, including thermal comfort and the psychological influences of comfort. This knowledge certainly falls in line with the wide array of benefits that Ebenezer Howard lists for the Garden City (Howard, 1898). Additionally, some of the key aspects of urban life that he mentions as detrimental to the urban dweller's quality of life include mental health concerns.

3.3 Methods

The redevelopment centers on the City's plans to increase tree canopy, change the housing structures to be higher density with mixed incomes (not just government housing), and expand Edison Park to create more space for physical activity and community gathering ("Choice Neighborhoods 2016 Implementation Grant Awards," 2016). Using the validated baseline case as our control, I converted the city's architectural redevelopment plans into an ENVI-met domain and simulated the same day (June 19, 2019) with the new neighborhood to examine the potential cooling impact of the redesign (Fig. 17).

The redesign increased the green space, tree canopy, and the size of Edison Park. The housing units are also updated to be more densely populated through the building of taller apartment and condo units (most are 3-4 stories compared to the current 1-2 stories). This results in a change of LCZ from LCZ 6 (open low rise) to LCZ 5 (open mid-rise). Roof albedo in the redevelopment is also increased as the material changes from a dark shingle to white (or off-white) flat roof coating. Some solar panels are being considered in the redevelopment plans; however, as the location and density are not finalized, they were removed from the modeled domain. The modifications to the neighborhood result in some changes to the overall land cover types. The redesigned domain is comprised of 45.0% impervious surfaces (asphalt and concrete), 13.1% buildings, and 14.4 % vegetated (grass and trees). The rest of the domain is either sand or loamy soil (Fig. 17).

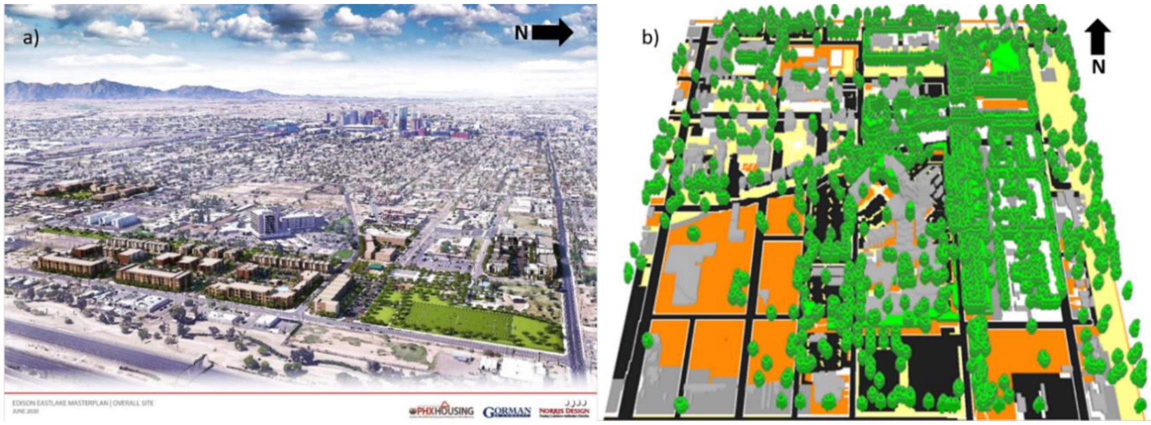

Figure 17 *– Edison Eastlake neighborhood redevelopment, a) is the architecture rendering of the whole neighborhood, b) is the redesign modeled in ENVI-met.*

Model output from the baseline model (discussed in detail in Chapter 2) and the redesign model are compared to assess the efficacy of the redesign for cooling the thermal environment. Using ambient air temperature and mean radiant temperature, hourly difference plots are created to visualize the magnitude and spatial difference between models. To estimate the overall impact of the redesign on the thermal environment, averages were calculated for each hour as well as for the entire simulated period. This analysis excludes initial hours of the simulation (4 -7 am) to allow for model spin up and post-sunset hours (after 8 pm) due to known issues with ENVI-met's estimate of heat storage and release pre-sunrise and post-sunset (Crank et al., 2020; Gál and Kántor, 2020; Mahmoud, 2011). This chapter focuses on model output from 8:00, 12:00, and 16:00 LST. The three hours selected allow for analysis of the morning impacts, peak insolation (which is an important component of T_{MRT}), and peak ambient air temperature times. Key design components included in the model are: (1) higher albedo roofing on new construction and (2) increased shading and vegetation for transit corridors through the neighborhood (the vegetation modeled is for the first few years immediately following installation). The tree canopy is assumed to be at 5 m in height with small crowns such as would be typical for the trees within the first five years of installation. Full maturity in the tree canopy would yield different results but those are more long-term results. Figures 3.3-3.4 detail the specific design features and are adapted from the design documents of the City of Phoenix Housing Department, and The Nature Conservancy: Nature's Cooling System Project, (Conservancy, 2019; Guardaro et al., 2020, 2019).

A key element of this analysis utilizes the redevelopment plans by the City. Figure 18 details the specifics around the plans for the neighborhood. Of note for the thermal environment, the Frank Luke homes (east of the hospital) and the Luke Krohn homes (northeast of the hospital) will be demolished and replaced with 3 and 4 story apartments and condos. These new units will be a mixture of government housing, low income, and middle-income housing designed to diversify the community and attract workers who seek an active transit lifestyle.

Figure 18 *– Detailed figures showing the redesign elements the City of Phoenix will use. These plans show a) the specific designs for the Frank Luke units, the Luke Krohn units, and Edison Park; and b) the overall neighborhood plan, including transit upgrades and other housing units that are being redeveloped.*

The major aesthetic changes are to the vegetation in the neighborhood. Edison Park (in the northeast corner of the neighborhood) is expanded to include more recreational activity sites, build a green space corridor to buffer between the new units and the hospital, and to connect the park to Van Buren Street via this corridor. The redevelopment will increase the tree canopy in the community with a bent toward creating inviting green space that can be utilized for active transit as well as community engagement space. Finally, a new apartment building is being constructed on the northern edge of the neighborhood, between Edison Park and Edison Elementary. These will also be 3-4 story apartments and have already been moving forward with construction (Fig. 19).

Figure 19 *– Current and ongoing construction of a) Edison Park and b) the new apartment units on the north edge of Edison Eastlake. Photo was taken by Peter J. Crank on August 18, 2020 from Edison Park, looking west.*

3.4 Results

Evaluation of Air Temperature

The previously discussed design elements were implemented in ENVI-met and modeled to examine their effectiveness as cooling grey and green infrastructure. Figures 19-22 show ENVI-met's results for air temperature at 8 am (Fig. 20), 12 pm (Fig. 21), and 5 pm (Fig. 22) on June 19, 2019. Overall, there is some cooling in the areas of redevelopment, particularly along the vegetated corridor where either it was bare soil (lower portion of the domain) or had housing units in place. The cooling extends to the north side of the apartment buildings, especially in the morning and late afternoon hours. The magnitude of the cooling in these locations is around 0.5-1.5 °C.

Cooling is more apparent in air temperature during the morning and afternoon hours. The redesign also has a downwind effect. While certainly weaker than the cooling seen directly beside the redesign elements, there is noticeable cooling to the north and east of all redesign elements, indicating that there may be some cooling benefits for areas downwind of the design. Table 7 documents the mean cooling for ambient air temperature (and T_{MRT}) across all hours of simulation. The overall effect was calculated as the smallest square that incorporated the new designs and its downwind effect. The overall effect is dampened by the inclusion of the hospital and other large portions where no change was made and small rounding errors lead to slight increases in air temperature over the roads and parking lots that remained unchanged. Additionally, some locations that had previously been within a building or just north of a building in the baseline case are now exposed to direct sun and subsequently are warmer than before Figures 20-22. This effect is particularly noticeable in the 12pm and the 5 pm output and these effects also create downwind warming effects that overspread areas where no change occurred.

Table 7 *– Overall effect in Edison Eastlake neighborhood of the redevelopment plans for air temperature and mean radiant temperature.*

Mean Difference Across Domain

Hour	Air Temperature (°C)	Mean Radiant Temperature (°C)
8am	0.037	-1.660
9am	0.044	-1.251
10am	0.058	-1.017
11am	0.077	-1.006
12pm	0.058	-0.881
1pm	0.059	-0.747
2pm	0.057	-0.896
3pm	0.073	0.000
4pm	0.078	-1.074
5pm	0.073	-1.507
6pm	0.074	-2.018
7pm	0.073	-2.194

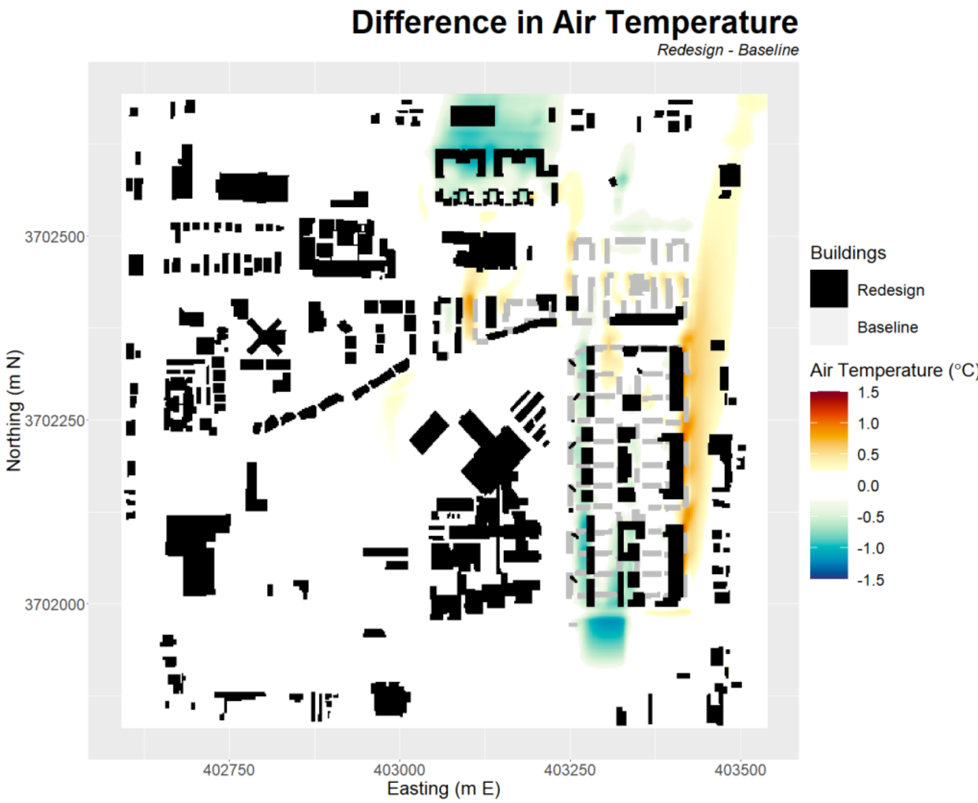

***Figure 20** – 8 am air temperature difference plots.*

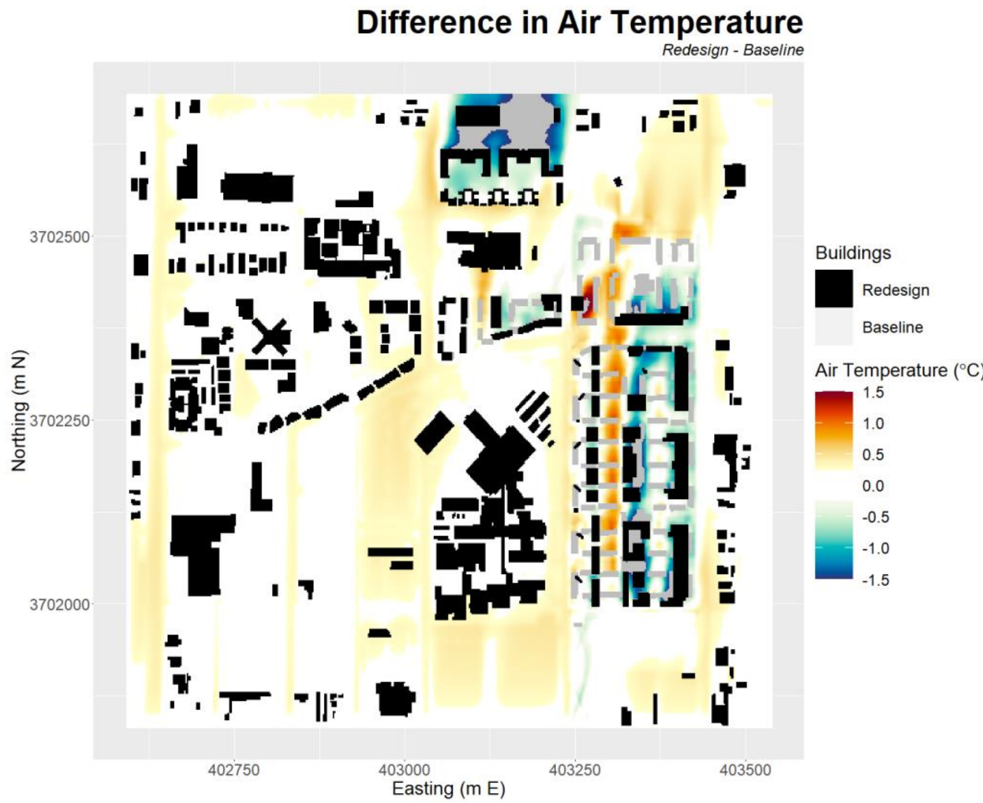

***Figure 21** – 12 pm air temperature difference plots.*

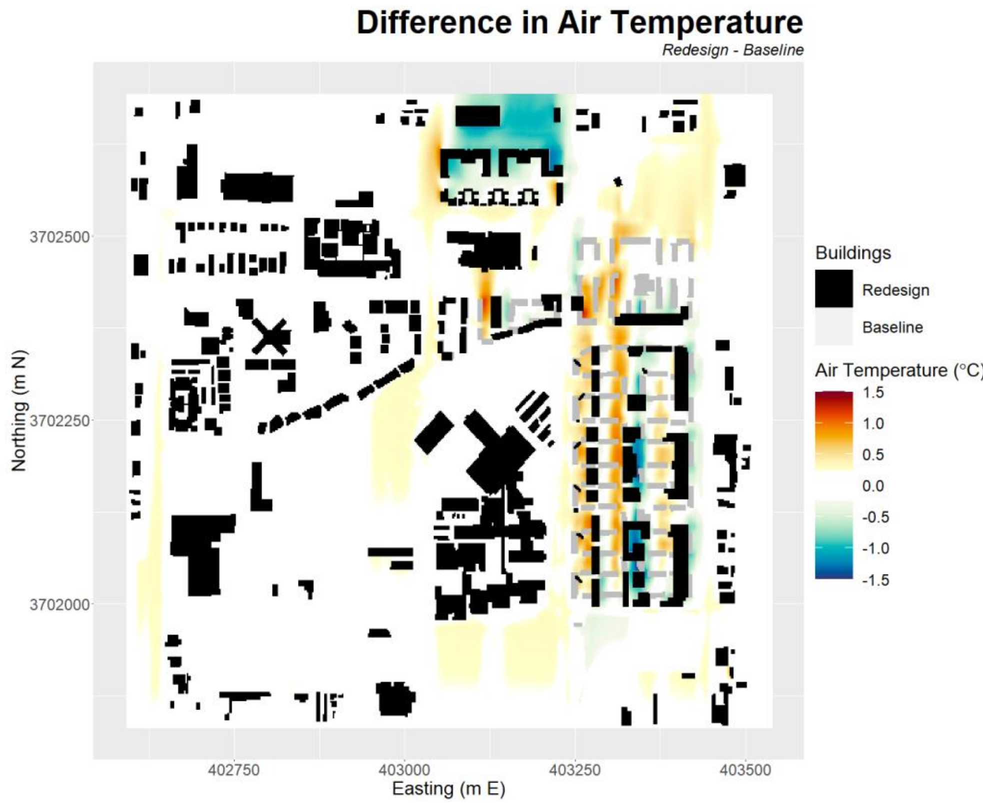

Figure 22 *– 5 pm air temperature difference plots.*

Evaluation of T_{MRT}

When examining the T_{MRT} redesign results, the magnitude of the cooling increases, as is expected when considering ambient air temperature compared to T_{MRT} (Figures 23-25). The cooling centers around the areas of shade at each hour. In particular, locations on the north side of buildings see the strongest cooling of T_{MRT}. There are some locations that see significant increases in T_{MRT}; however, those locations are mostly on the south-facing side of structures that are in locations which either had bare soil or grass before. As such those locations are expected to increase relative to the previous design. Tree cover provides limited T_{MRT} cooling, yet the trees themselves, as modeled, are only a few years old and as such have not grown into full maturity yet.

While local effects of tree cover greatly impact both air temperature and T_{MRT}, any downwind effects are limited to air temperature. The large impact tree cover does have on T_{MRT} indicates the radiative load in the shade is significantly less than that of sun exposure and the pervasiveness of these shaded spaces would provide widespread shelter from the harsh summer sun. The overall effect on the neighborhood in terms of T_{MRT} is a slight cooling effect (Table 7), yet pockets of greater thermal benefit are in close proximity to grey and green shade infrastructure.

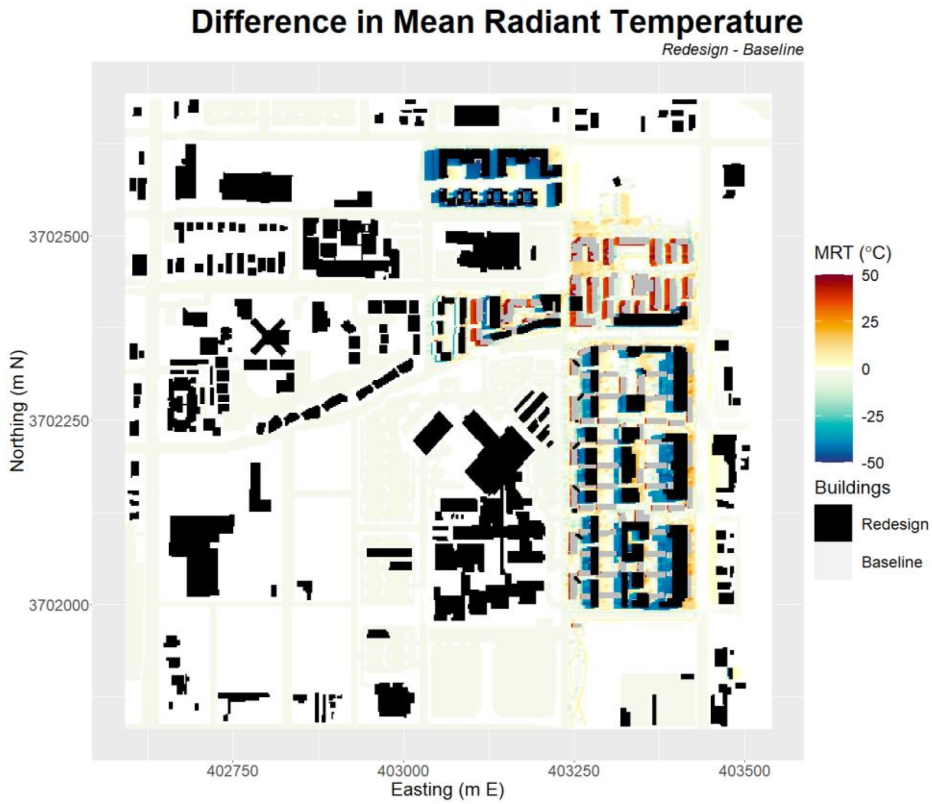

Figure 23 *– 8 am mean radiant temperature difference plots.*

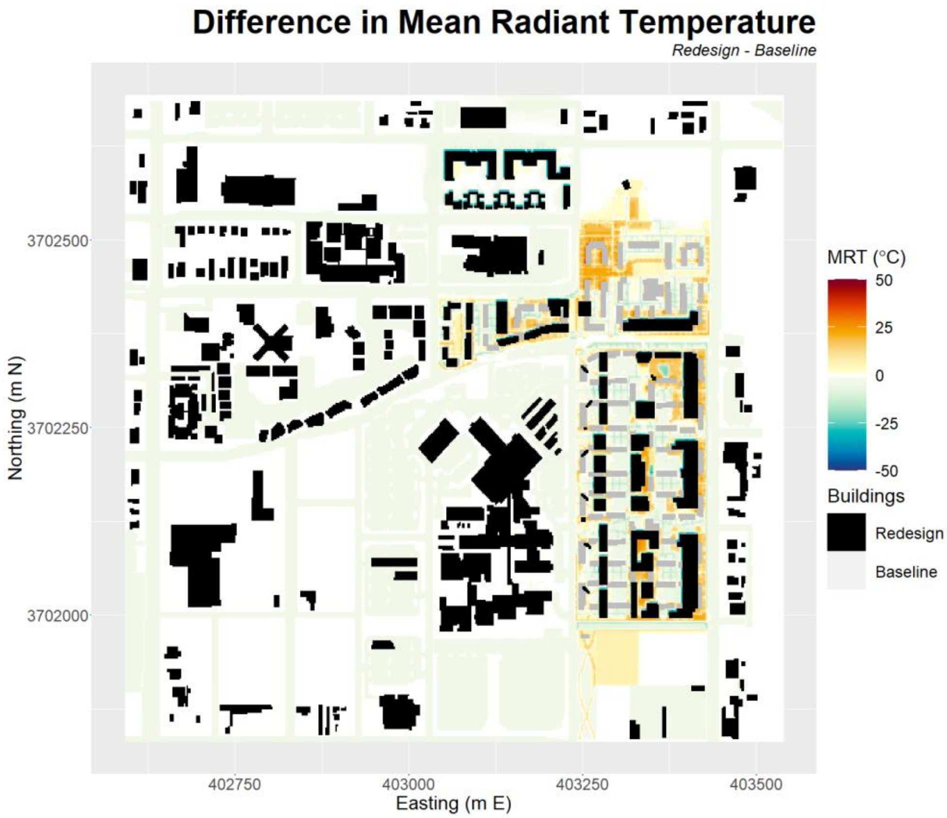

Figure 24 *– 12 pm mean radiant temperature difference plots.*

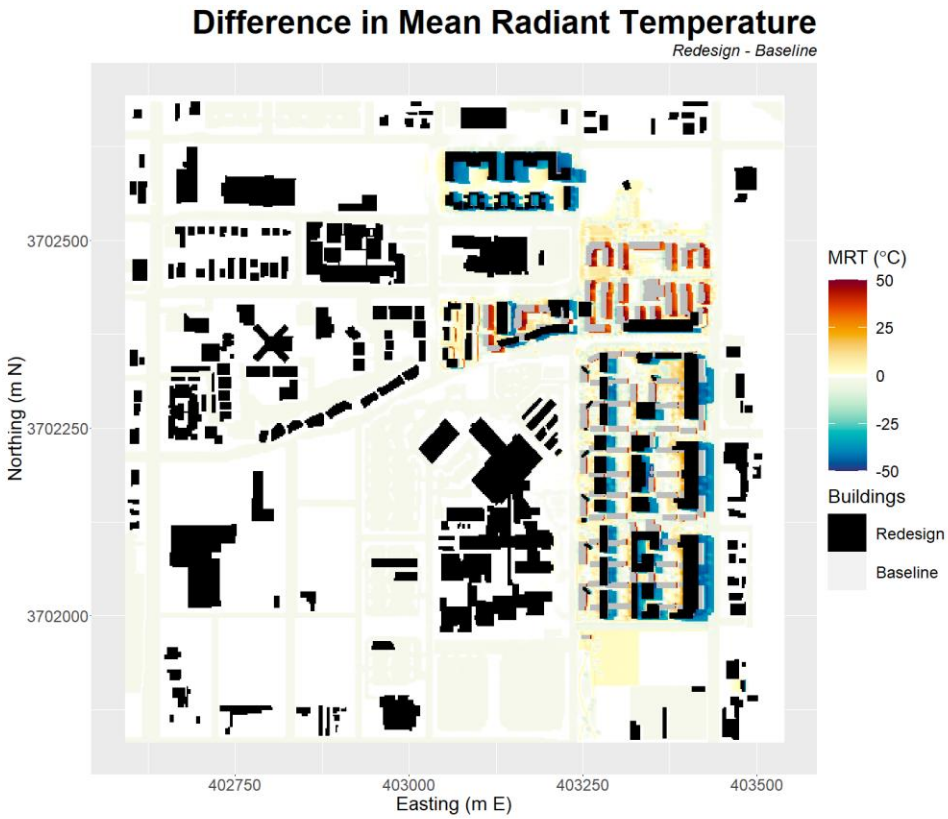

***Figure 25** – 5 pm mean radiant temperature difference plots.*

3.5 Discussion

Thermal Environment Impacts of the Redesign

The redesign with its increased building density, building height, increased green space, young tree canopy, and cooling grey infrastructure is modeled by ENVI-met to have some modest benefits to the thermal environment. Specifically, T_{MRT} is improved in locations where green or grey shade structures are in place. Shade is one of the keys to improving T_{MRT}, but is also one of the most challenging components of a complex urban climate for ENVI-met to model (Crank et al., 2020; Gál and Kántor, 2020). Ambient air temperature is also improved with pockets of cooling that are similar to what others have found through empirical studies of green space for cooling (Bowler et al., 2010; Santamouris et al., 2018). The downwind effect of the redesign is apparent, though the magnitude of its effect over longer distances is unclear given the constraints of the model. Nonetheless, the approximate distance (50-100 m) is in line with previous research on downwind cooling from targeted heat mitigation strategies (Crank et al., 2018; Eliasson and Upmanis, 2000; Ng et al., 2012; Taleghani et al., 2019).

Generally, the redesign has a slight cooling impact on the thermal environment based on ENVI-met modeling. This supports the City's intent to provide thermal benefits to the community. Residents had expressed desire for more shade while maintaining a safe environment (Conservancy, 2019; Guardaro et al., 2020, 2019). These expressed desires were addressed through the vegetated corridor as the design includes cooling grey as well as the green infrastructure that can be utilized to foster a tighter community while still providing the cooling benefits necessary to allow for outdoor community interaction during the summer months.

Areas where the model indicates warming (such as the south, east, and west facing walls) may be locations where further shade infrastructure might be added to provide further improvement to the thermal environment and reduce the energy burden of residents living inside these units. Another potential temporary intervention would be to install grey shade infrastructures such as shade sails to create cooler conditions over the tree canopies. This could provide similar thermal benefits as full grown trees to residents, but also serve to help the trees grow and thrive in the harsh summer sun of Phoenix.

Limitations and Future Research

Of note, the dry conditions in a hot arid environment make green space cooling a challenge to model. Additionally, the tree canopy modeled is for the first few years after redevelopment completion with a canopy at a height of only 5 m and minimal crown. Thus, the actual redesign may over-achieve relative to these results as the grass will be irrigated providing additional evaporative cooling to the environment, converting more of the incoming solar radiation into latent heat flux, instead of converting to sensible heat (thus warming the surface and subsequently the ambient air). These two limitations in the modeling prevent evidence of greater cooling potentials. The ability to make assumptions on the cooling of the thermal environment relies on the use of the delta method which is commonly used in global climate modeling studies and some micro, meso, and regional studies as well (Hijmans et al., 2005; Jandaghian, 2018; Navarro-Racines et al., 2020; Shick Lee et al., 1992; Wu et al., 2018). Further improvement of the model is necessary to examine the impact slight changes in soil moisture and the potential of irrigated surfaces in ENVI-met. This work could aid in verifying the regional work of Georgescu et al. (2014) as to the possibility of urban heat mitigation serving to negate projected climate changes.

The model was not run for overnight hours. As such, the nocturnal impacts of the increased vegetation were not explored, which limits the generalizability of the redesign as modeling efforts did not consider whether or not the green space and tree canopy would elevate minimum temperatures due to evapotranspiration. However, the model does not permit buildings to retain heat once the solar radiation is removed from the model (i.e., at night). As such, ENVI-met is insufficient at modeling overnight conditions in urban areas; therefore, ENVI-met was not and should not be considered until that parameterization in the model is updated and the question of overnight thermal environmental conditions from green space is left unaddressed.

The model would benefit from more information driving the model. The current configuration struggles to handle the forcing of variable wind speed, wind direction, or solar radiation when using large domains. These variables play a vital role in the variability of urban climate. Phoenix, as well as some other cities, have a significant wind shift during the day, particularly in the summer. Due to the city's position next to the Superstition Mountains, the early morning hours are dominated by an easterly breeze, but this flips in the afternoon to a westerly breeze. Additionally, the desert landscape surrounding the city lends itself to stronger winds resulting from outflow boundaries of storms around the region. Thus, the wind component to the model is significantly lacking. Additionally, the model parameterizes soil moisture to be constant across the domain. This is problematic when examining an urban space that has streets, sidewalks, bare soil, and grass within the domain. Each of these surfaces will have very different soil moisture contents, and this becomes increasingly noticeable and influential in hotter and drier climates such as Phoenix.

Finally, this model is limited to estimating the cooling based on conditions measured with the existing neighborhood design. To fully understand the effectiveness, future work must be done to collect data on the ambient environment once the redevelopment is complete. This future work can then reassess the ENVI-met model to determine how representative the model currently is to the design plans. The evaluation only considered the plans the city is using in their redevelopment. Future work could build on this and explore how different design elements might have performed better than the final plan. These lines of research could consider the implementation of solar panels, reconfiguration of the buildings to create more of an enclosed green space, and even an addition of blue infrastructure (such as a pond or pool) to determine its effectiveness at cooling the neighborhood.

By examining the redevelopment plans by its fitness for use in cooling the thermal environment, this study determined moderate effectiveness. Yet, urban heat mitigation was not the primary intent of this redevelopment. Certainly, the city considered the dire need for cooling in this neighborhood when they proposed the redevelopment to HUD ("Choice Neighborhoods 2016 Implementation Grant Awards," 2016); however, a reframing or refocusing the redevelopment through the lens of urban heat mitigation might have resulted in different approaches to how they determined the plan.

A significant portion of thermal comfort and perception of heat risk is subjective and dependent on the psychological, physiological, and behavioral composition of the individual (Middel et al., 2016; Nikolopoulou et al., 2001; Nikolopoulou and Lykoudis, 2006). The use of the community workshops is a first step in incorporating this piece to the puzzle that is thermal environments (Conservancy, 2019; Guardaro et al., 2020, 2019); yet, the plan falls short of explicitly incorporating green infrastructure and cooling grey infrastructure as a central tenet to the redevelopment. The result may well have been something more akin to what Ebenezer Howard envisioned with his Garden Cities of Tomorrow (Howard, 1898) and certainly would have sought to minimize the horizontal space dedicated to vehicular traffic.

3.6 Conclusion

Using the redesign plans from the City of Phoenix, the Edison Eastlake neighborhood redevelopment was modeled in ENVI-met and compared to the baseline model to assess the efficacy of the redevelopment at providing thermal benefits from the environment to the community. The results show modest cooling of the general neighborhood, with pockets of cooling on the order of 0.5-1.5 °C for ambient air temperature. T_{MRT} cooling was isolated to locations with new trees and artificial shade structures, yet in particular the results show cooling in the vegetated corridor and between apartment buildings in the redevelopment. Results confirm the possibility of cooling through redevelopment, yet there is a limit to impact of the redesign for immediate cooling of the thermal environment. More work on the model and post-redevelopment measurement are necessary to make the final call on the Edison Eastlake redesign's efforts to cool the neighborhood.

As the redevelopment takes place, there is a continued need to engage the community in the process, seeking to better understand their needs and why those needs exist. Post-redevelopment analysis can aid in determining the effectiveness of the plan for addressing those community needs. The benefit or burden of this redevelopment will still land squarely on the shoulders of those living in this neighborhood, and an aspirational hope for this is to mitigate prior environmentally racist practices, but the success of this still remains to be seen. Regardless, the study suggests that cooling is possible and as such, the City can use their design plans to cool the neighborhood (even just slightly) and begin to address the broader concerns that residents have in Phoenix of thermal inequity and the need for neighborhood planning that is designed for the benefit of all. This study can also be used to aid the City in identifying areas and methods for fine tuning their design to provide shade elements for pedestrian hot spots as well as to reduce energy costs in the hot summer months. Using green and grey shade infrastructure to improve the thermal environment of a neighborhood could provide cooling to the outdoor environment, as found in this chapter, in addition to various other community benefits such as lowered energy costs in the summer, community engagement, and nature contact.

CHAPTER 4

MENTAL HEALTH AND HEAT: A DISTRIBUTED LAGGED NON-LINEAR MODEL APPROACH TO RISK AND MITIGATION FOR SCHIZOPHRENIA HOSPITAL ADMISSIONS

4.1 Introduction

The effect of extreme temperature on a variety of mortality and morbidity outcomes has been extensively examined (Fouillet et al., 2006; Gasparrini et al., 2012; Sheridan et al., 2009). Much of the research is focused on physiological impacts of temperature (increased core temperature, cardiovascular distress, etc.). But, research also indicates neurological and psychological processes/outcomes are susceptible to heat (Höppe, 1999; Lin, 2009; Salerian et al., 2008; Semenza et al., 2008; Sharma, 2007). Yet, throughout the literature, the psychological impacts of extreme temperature have been understudied. In light of increased awareness of environmental factors on mental health (Frumkin, 2003; Maller et al., 2006), I seek to better understand the interactions of weather and mental wellbeing in urban areas.

Attention to the environment as a determinant for public health has been steadily growing for the past several decades; however the introduction of the conceptual approach to environment and mental wellbeing was made centuries ago and is being revived in the literature (Frumkin, 2003; Maller et al., 2006). Among environmental hazards, extreme heat has been a primary concern, motivated in part by projections of higher temperature across the globe in the coming decades. The negative impacts of extreme heat have been broadly documented for society and for the physiological health of humans (Gosling et al., 2009; Harlan et al., 2006; McGregor and Vanos, 2018). Additionally, sociologists and psychologists have noted the impact of urbanization on human health psychologically (Lewis, 1992; March et al., 2008). The increased urbanization and warming across the globe are concerning for public health and understanding the relationship between these two coincident environmental variables on the mental wellbeing of urban dwellers is vital to public health preparations for future cities and climates. This study adds new knowledge to this space in understanding how heat can interact with mental health and proffers some methods for decreasing the public health burden on the community.

Causal Pathway of Schizophrenia and Extreme Heat Vulnerability

Schizophrenia blocks the neurotransmission of information to and from the anterior hypothalamus in the temporal lobe of the brain (Hasegawa et al., 2005). This portion of the brain is a critical communication center in regard to thermoregulation (Roelands and Meeusen, 2010). Thus, schizophrenia blocks communication from the brain to other bodily functions, preventing the body from engaging its natural mechanisms for cooling (sweating) and heating (shivering) (Hasegawa et al., 2005). Therefore, without medication, persons who suffer from schizophrenia are at a higher risk than the general population for heat-related illnesses when faced with extreme heat conditions (see Figure 26).

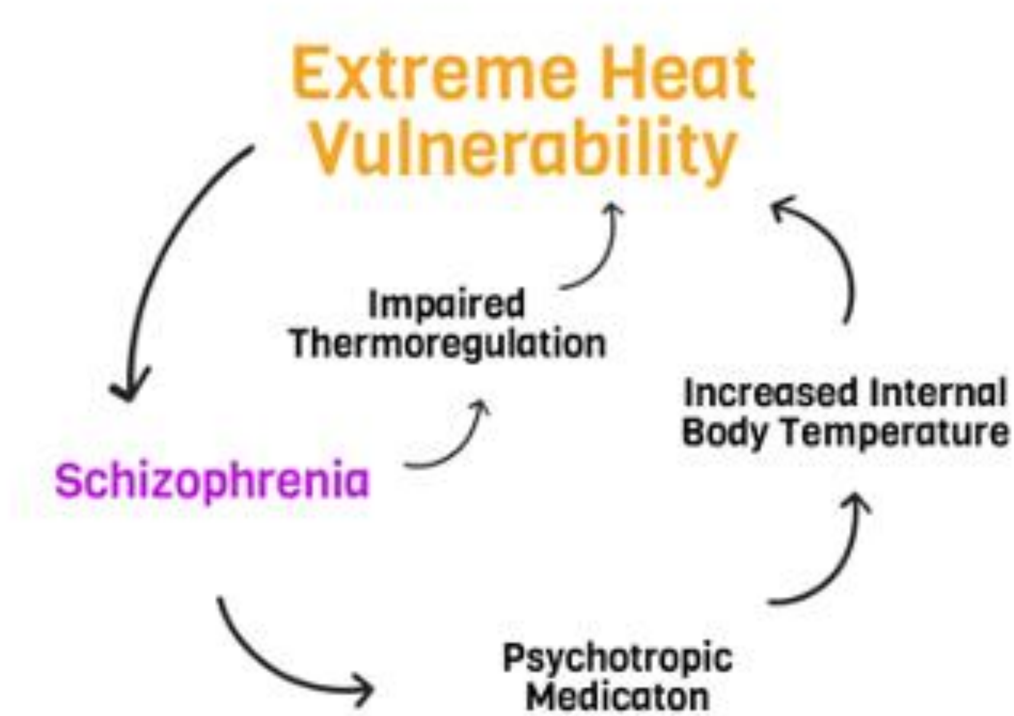

Figure 26. *Causal pathway for schizophrenia to extreme heat vulnerability.*

Medication for schizophrenia is effective at reopening the channels of communication within the brain when taken as prescribed. However, these psychotropic medications have a well-known side effect of increased internal body temperature (Martin-Latry et al., 2007; Nordon et al., 2009). While this side effect may be inconsequential in some instances, it can put individuals with schizophrenia who are on their medication at a higher risk for heat-related illnesses, because their body temperature is closer to thresholds for physiological heat strain (0.5-1 °C). In total, then, there are two well-known biological-neurological mechanisms that elevate the risk of heat illness for those with schizophrenia.

Separately, some researchers have suggested that high temperature can be a driver of certain psychological outcomes/disorders. Multiple studies have presented statistical associations between increased ambient air temperature and aggression and irritability (Anderson, 1989; Kuo and Sullivan, 2001; Page et al., 2007). The environmental effects on human temperament and psychology point to a partially quantified relationship between extreme high temperature and a destabilization of mental health. Not only are individuals with psychological disorders more susceptible to adverse effects from high temperature, but high temperature may also trigger adverse psychological events. In this adverse positive feedback mechanism, extreme heat can affect a person's ability to manage their own mental health. If unable to cope, a person may cycle into crisis mode which can result in hospitalization for either the disorder or for heat exposure due to the inability to communicate thermoregulatory needs of the body to the brain.

Previous research uses hospitalization data and daily average temperature to examine the relationship between temperature and mental health (Hansen et al., 2008; Kim et al., 2014; Sung et al., 2013, 2011; Wang et al., 2014). Each found an association between increased ambient air temperature and hospitalization for mental or behavioral health disorders in Australia, South Korea, Taiwan, or Canada. Other research has considered the impact of solar radiation on the mental health of the community; however, the results are inconclusive (Aviv et al., 2011; Shiloh et al., 2005; Volpe and Del Porto, 2006). In many instances, high temperature and/or solar radiation have been connected to increased mental health concerns, with the exception of studies in Israel (Shiloh et al., 2009, 2005). Yet, the inflection point at which risk significantly increases varies drastically from location to location. Studying the effect of heat waves on mental health in Adelaide, Australia, Hansen et al. (2008) found that for various mental health disorders (ranging from dementia and senility to psychoactive substance use and schizophrenia) heat waves are related to increased admissions for all disorders with an inflection point for schizophrenia of a maximum temperature of 35 °C. In a study of ambient temperature and emergency room hospital admissions in Toronto, Canada, Wang et al. (2014), found an inflection point in relative risk for all mental and behavioral disorders at a daily mean temperature of 32 °C. Given that most of the research is in humid temperate or tropical climates, little is known about how a dry and hot climate with little reprieve from solar radiation through cloud cover impacts mental health.

Given the abundance of evidence that temperature-mortality and temperature-morbidity associations vary from place to place as a function of geography and climate (Curriero et al., 2002; Guo et al., 2017; Sheridan et al., 2009), I anticipate that the association between temperature and mental health events may also differ between chronically hot and arid regions and the mid-latitudes, temperature climates that have been the subject of the limited body of previous research on this topic. Under increasing global temperature and urbanization, more of the US and global population will be living in extremely hot and arid cities in future decades (Revi et al., 2014). Therefore, I sought to understand the nature of the temperature-schizophrenia association for a large city in a hot, arid climate. I posit that there would exist some disparity in relative risk associated with temperature based on age, ethnicity, and gender. I expect increased risk for younger and older populations, non-White ethnicities, and for males.

4.2 Methods

Phoenix, Arizona is a major US city in Maricopa County (the 4th most populous county in the United States) with just over 4 million residents (Census, 2010). Additionally, Phoenix is one of the fastest growing metropolitan regions in the United States. Phoenix has a hot desert climate (BWh) with extremely long, hot summers and short, mild winters (Kottek et al., 2006). Maximum daily temperature exceeds 40 °C for the majority of the summer.

To study the direct effect of environmental heat on mental health, I collected health data from 2006-2014 from the Maricopa County Department of Public Health. I specifically extracted daily counts of hospital admissions with ICD-9 codes 295.0-295.999 in any position on the case diagnosis list. I included codes for all types of schizophrenia. The record included a total of 86,699 cases. Across the time period studied, the average daily count of hospitalizations increased from ~20 per day to ~40 (Fig. 27).

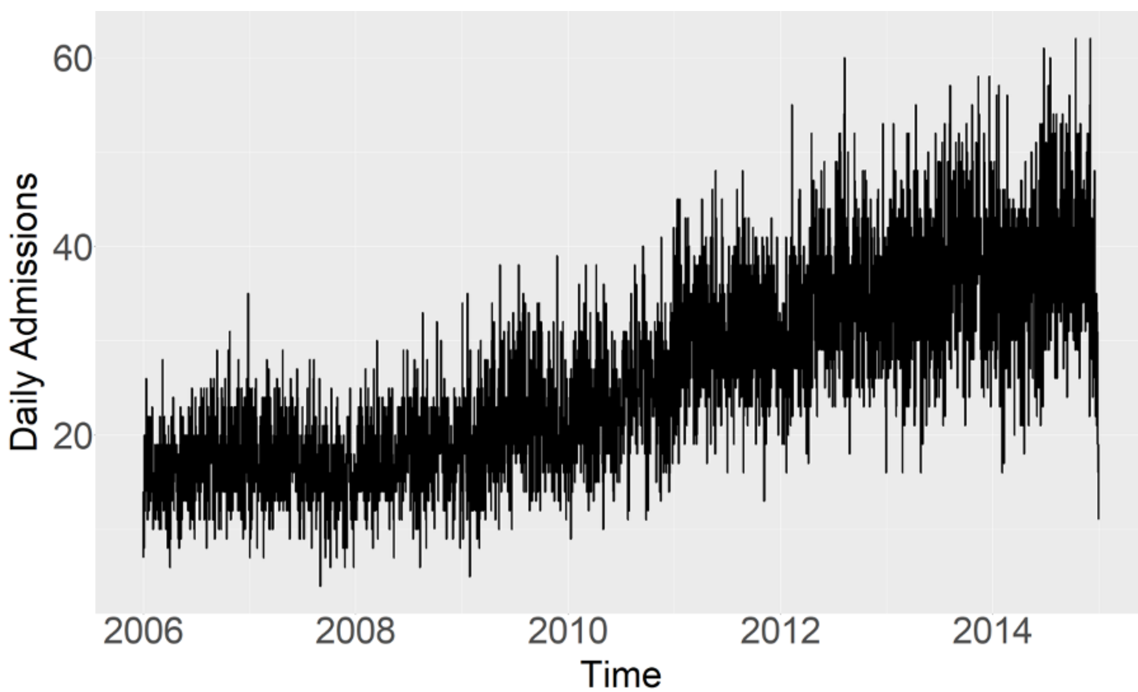

Figure 27. *Daily incidence of Schizophrenia in Maricopa County hospitalization records from 2006-2014 using ICD-9 295.0-295.999 codes dataset.*

Daily atmospheric data was obtained from the DW4174 Mesa Weather Station through the MesoWest network (mesowest.utah.edu). The weather station is located in Mesa, Arizona (111.8608° W, 33.4005° N). The area surrounding the weather station is suburban neighborhoods with a nearby community college about 0.4 kilometers to the south. The DW4174 record includes daily summary of data, including average, maximum, and minimum temperature. The dataset was complete with no missing days in the study period (2006-2014). This dataset was selected because of the access to solar radiation data as well as being representative of the suburban sprawl that characterizes Phoenix (LCZ 5 and 6). Over the time period (2006-2014), there was no substantial change in temperature at this site.

We conducted analyses based on the full data set as well as subsets based on gender, age, ethnicity, and location of the schizophrenia code (first position or all other positions). I measured the association between daily temperature and schizophrenia hospitalizations using a distributed lag non-linear model (DLNM) in the statistical software R (version 3.5.1) (Gasparrini et al., 2012, 2010).

In the DLNM framework, I modeled the daily count of schizophrenia hospital admissions as a function of temperature, accounting for long-term and seasonal time trends and holidays. One of the key advantages to the DLNM is that it can be used for examining the lagged effect of the environmental hazard on the outcome of interest. Equation 4.1 denotes the fundamental equation where Y_i is the expected hospitalization as a logarithmic function of an intercept (α) a time lagged response (day zero to day ten) variable (β) for daily temperature (t_i) and the summation of a function (g_k) describing the influence of confounders (x_{ki}).

$$log(Y_i) = \alpha + \beta(t_i) + \sum_{k=1}^{K} g_k(x_{ki})$$

Eq. 4.1

Temperature was the primary independent variable of interest. I modeled the effect of daily temperature on hospital admissions using a natural cubic B-spline with 4 degrees of freedom. I examined the lagged effects out to 10 days using 4 degrees of freedom for the lagged effects. To test for differing influences of day versus night exposure, I generated separate models based on daily maximum, daily mean, and daily minimum temperature. I controlled for seasonality and long-term time trends in schizophrenia hospital admission counts by including time in the model, represented as the sequence of integers from 1 to 3289 (the length of the study period).

Following guidance from the literature, I applied a natural cubic B-spline for the time term with 7 degrees of freedom per year (Armstrong, 2006; Barnett et al., 2010; Rocklov et al., 2012; Wang et al., 2014). In sensitivity analyses, I tested the effect of adjusting the degrees of freedom for the time term to 3, 5, and 9. Holidays were included as a factor variable by creating an additional variable that denoted whether or not each day was a holiday, with differing weights based on the significance of the holiday (e.g., major holiday versus minor holiday in the United States). To assess model performance, I extracted the Quasi-Akaike Information Criterion (QAIC) from models specified as described above assuming a Poisson distribution. However, because the hospitalization data were over dispersed, the final models that I calculated assumed a quasi-Poisson distribution.

We subsequently estimated temperature-attributable morbidity based on the distributed lag nonlinear models that I generated using a backwards calculation (looking at the risk as a result of past exposures) with the 'attrdl' function in R (Gasparrini et al., 2015; Gasparrini and Leone, 2014). Similarly to Adegboye et al. (2019) as well as Onozuka and Hagihara (2015), I used a backward attributable risk to quantify the proportion of schizophrenia hospital admissions that could be linked to deviations in temperature from a statistical optimum. The data were split into three ranges (cold, temperate, and hot) with cut points at the minimum relative risk from the DLNM and the 67th percentile of minimum temperature to group the data for attributable risk analysis.

Finally, I multiplied the number of attributable cases by the average cost of schizophrenia hospitalizations in the United States (Stensland et al., 2012) to estimate the total healthcare costs from high temperature-driven schizophrenia hospitalizations in the study region. Stensland et al. (2012) estimated that in the United States, the average uninsured schizophrenia patient's stay at a hospital costs to be $5707 USD (with insured patients costing over $7000). The uninsured patient is also found to have a shorter stay than the insured. Therefore, using the lower bound of their results, I estimate the additional cost burden heat-related schizophrenia hospitalizations are having on Maricopa County healthcare providers. While the number of insured was significantly higher than uninsured in the study (85% to 10%), I want to make a conservative estimate of the cost burden as the Stensland study (2012) used data from the entire United States, not just Arizona or the Phoenix metropolitan area.

4.3 Results

There was a clear and significant effect of air temperature on schizophrenia admissions in Maricopa County, Arizona, after controlling for time and holidays. The association was slightly stronger for minimum temperature than for maximum temperature, based on the increased relative risks at both extreme warm and cold minimum temperature and a slightly lower QAIC value for minimum temperature than for maximum temperature (14,848 versus 14,851). For maximum temperature (Fig. 3) and minimum temperature (Fig. 4) I found similar shapes to the 3-dimensional surface of risk.

Both variables resulted in increased relative risk for extreme high temperature and extreme low temperature in the short term (day 0-2) and a weaker but still substantial increase in the long term (day 9-10). Under colder conditions, I also observed an increase in relative risk at day 0-2, 8-10, though these increases were constrained to the tail end of the temperature distribution. Minimum temperature, I found an inflection point at about 30 °C for day 0 and day 1 lag, above which hospitalization rates increased rapidly (Fig. 5). The inflection point of 30 °C remains relatively constant across the lag structure of the temperature-hospitalization association. For context, 30 °C is the 82nd percentile minimum temperature during the months of June, July, and August in the study region. Thus, for several weeks of each hot and long summer in Phoenix, the metropolitan area was at an elevated risk for hospitalization due to schizophrenia. Using maximum temperature showed increased relative risk for conditions above 40 °C for all days beyond the day it occurred (day 0).

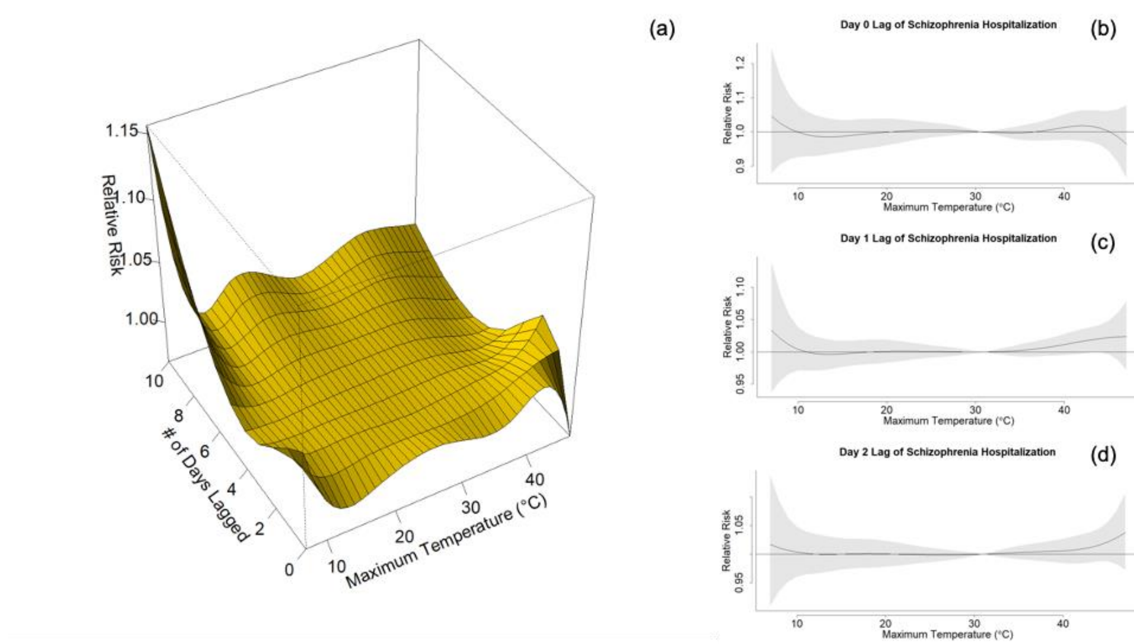

Figure 28. *Relative risk for hospitalization for schizophrenia due to maximum temperature. (a) A 3-dimensional surface plot of relative risk for hospitalization of schizophrenia at all maximum temperature for all (day 0-10) lags. (b) The relative risk graph of maximum temperature at day 0 lag. (c) The relative*

risk graph of maximum temperature at day 1 lag. (d) The relative risk graph of maximum temperature at day 2 lag.

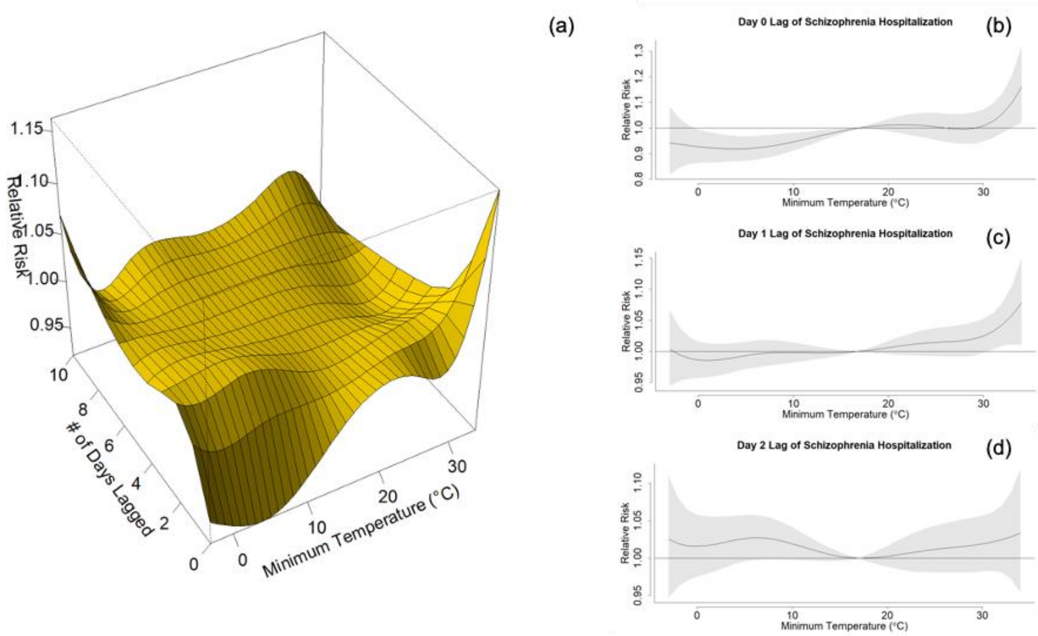

Figure 29. *Relative risk of hospitalization for schizophrenia due to minimum temperature in Phoenix. (a) A 3-dimensional surface plot of relative risk for hospitalization of schizophrenia at all minimum temperature for all (day 0-10) lags. (b) The relative risk graph of minimum temperature at day 0 lag. (c) The relative risk graph of minimum temperature at day 1 lag. (d) The relative risk graph of minimum temperature at day 2 lag.*

We did not find any significant associations between temperature and schizophrenia hospitalizations for subsets of the study sample based on age, ethnicity, or gender (Fig. 30-32). Qualitatively, the shape of the association for whites and nonwhites were slightly varied under colder conditions with a steeper curve toward increased relative risk under colder conditions and non-whites having a slightly higher relative risk under warmer conditions (Fig. 31). The shape of the association for younger and older patients also had small differences in shape, mostly in the extreme cold and warm conditions. Older patients (65 and over) had a lower relative risk in colder conditions but higher in warmer conditions than young patients (ages 0-17) (see Fig. 30). The shape of the association seemed to vary between women and men, with a higher risk for women and high temperature relative to men—but in neither case was the association significant (Fig. 32). I also found that the position of the diagnosis code (first code used or somewhere within the code list) had a small effect on the results, with slightly decreased relative risk below 10 °C and above 40 °C when only considering the first position diagnosis (Fig. 33).

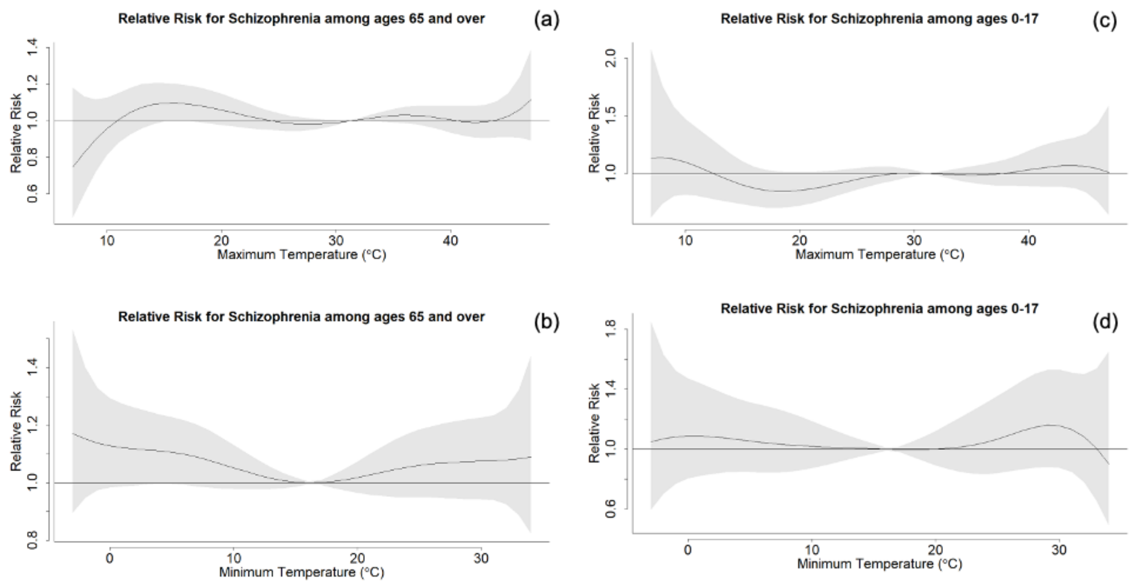

Figure 30. *Relative risk for older and younger patients. (a) Risk for schizophrenia hospitalization among patients aged 65 and older due to maximum temperature. (b) Risk for schizophrenia hospitalization among patients aged 65 and older due to minimum temperature. (c) Risk for schizophrenia hospitalization among patients aged 0 to 17 due to maximum temperature. (d) Risk for schizophrenia hospitalization among patients aged 0 to 17 due to minimum temperature.*

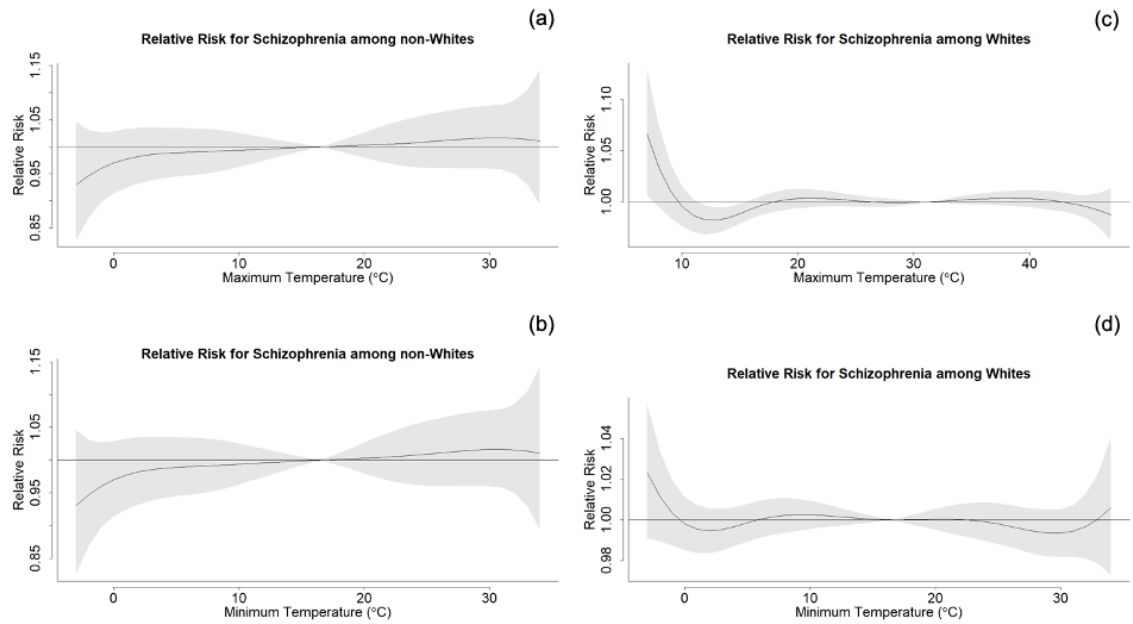

Figure 31. *Relative risk for patients by ethnicity. (a) Risk for schizophrenia hospitalization among non-White patients due to maximum temperature. (b) Risk for schizophrenia hospitalization among non-White patients due to minimum temperature. (c) Risk for schizophrenia hospitalization among White patients due to maximum temperature. (d) Risk for schizophrenia hospitalization among White patients due to minimum temperature.*

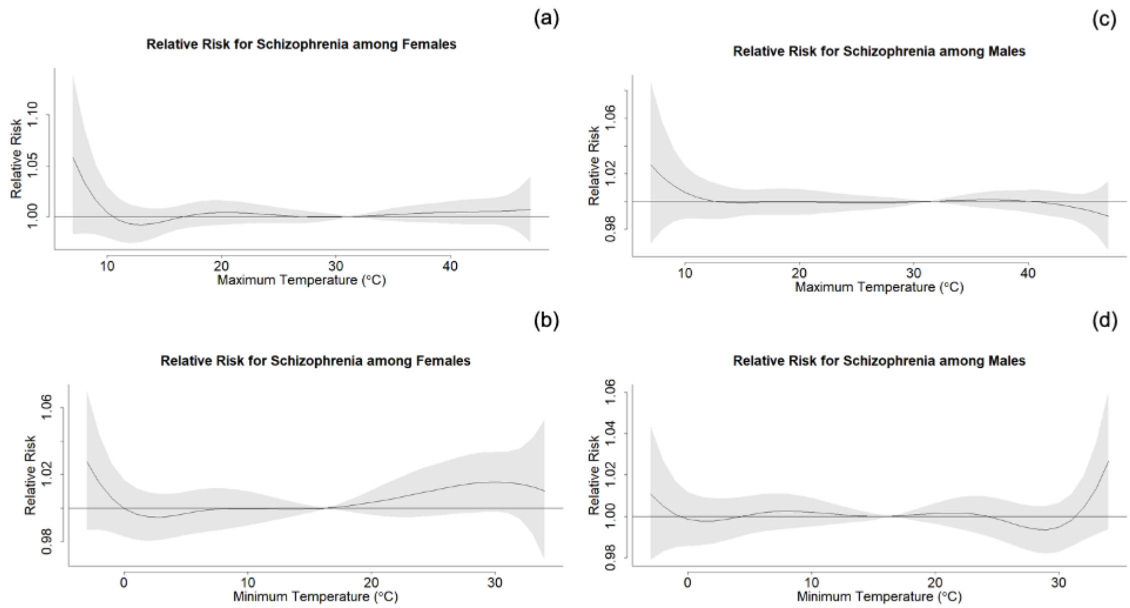

Figure 32. *Relative risk for patients by gender. (a) Risk for schizophrenia hospitalization among female patients due to maximum temperature. (b) Risk for schizophrenia hospitalization among female patients due to minimum temperature. (c) Risk for schizophrenia hospitalization among male patients due to maximum temperature. (d) Risk for schizophrenia hospitalization among male patients due to minimum temperature.*

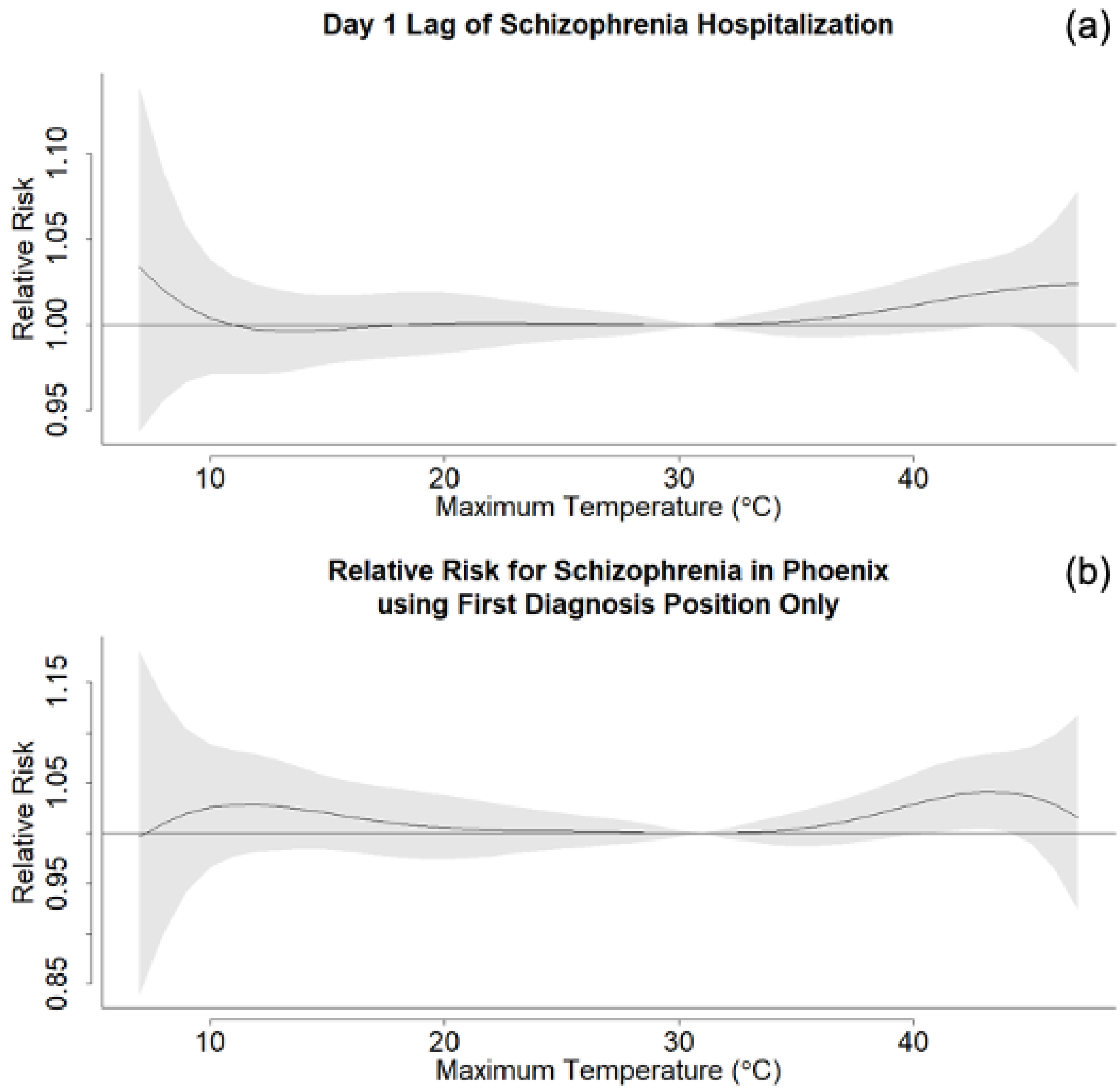

Figure 33. *Relative risk for patients by position of diagnosis code. (a) Risk for schizophrenia hospitalization for patients with any diagnosis position due to maximum temperature. (b) Risk for schizophrenia hospitalization for patients with first diagnosis position only due to maximum temperature.*

We estimated temperature-attributable schizophrenia hospitalizations using the model based on minimum temperature with an inflection point of 4 °C. I found that non-optimal minimum temperature accounts for 5.95% of the cases in the study period (CI: -2.21-13.21%). I then split the data into high and low temperature conditions (Fig. 34). To do this, I established a cold minimum temperature threshold of 3 °C and a hot minimum threshold of 22 °C. The low temperature threshold corresponds to the minimum morbidity temperature (lowest relative risk for hospitalization associated with minimum temperature) in the DLNM. The high minimum threshold uses the 67th percentile of minimum temperature in the data. When looking at high temperature, the attributable risk drops to 2.87% (CI: -2.05-6.85%) of the cases. Therefore, out of the 86,699 cases, around 5159 cases can be attributed to non-optimal minimum temperature (using the total attributable risk, not just high minimum temperature).

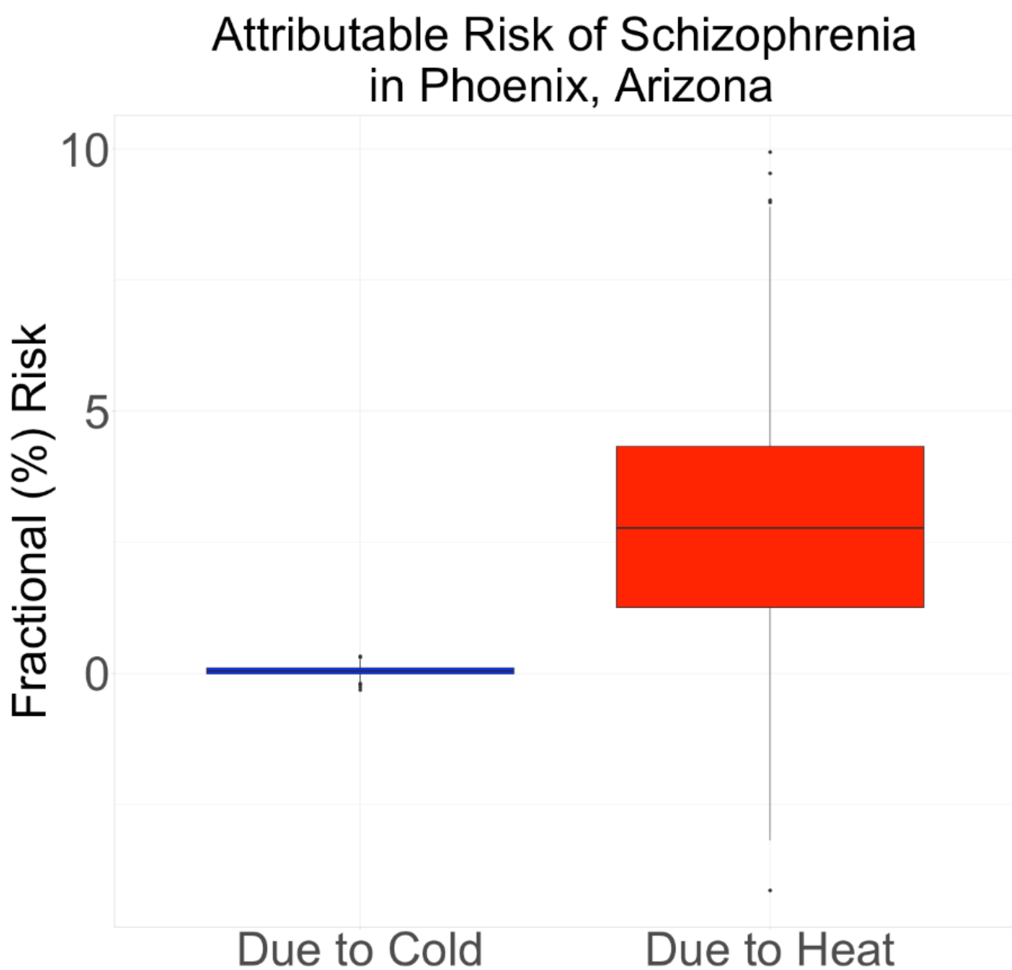

Figure 34. *Attributable risk due to high and low temperatures. The boxplot shows the estimated attributable risk of schizophrenia hospitalization from hot or cold minimum temperature. Cold was*

defined as minimum temperature below the minimum morbidity temperature (3°C) and hot was defined as minimum temperature warmest third of the dataset (22 °C).

For every case attributable to heat, at least $5707 (in 2006 USD) in schizophrenia-related healthcare costs are incurred (Stensland et al., 2012). I found a mean annual cost of $3.27 million associated with the hospitalization for schizophrenia due to ambient temperature or $29.44 million for the entire study period. When examining the impact of temperature on healthcare costs: low temperatures account for ~$275,000/year, moderate temperatures account for ~$1.67 million/year, and high temperatures account for ~$1.58 million/year.

4.4 Discussion

High and low minimum temperature in Phoenix increase the risk of schizophrenia hospitalizations. Specifically, when conditions result in minimum temperature above 30 °C, I see the risk sharply increase. I also found ~2.87% of the cases in the study can be attributed to high minimum temperature in Phoenix. This increase is most apparent in the short term (days 0-2); yet, there is also a noticeable increase at days 9-10. This longer-term increase is potentially due to the increased percentage of the summer months that are spent with 9-10 days of minimum temperature being at elevated levels. Ultimately, the cost of these hospitalizations (high or low minimum temperature) are estimated to be about $3.2 million per year in Maricopa County. These results are consistent with previous research (Hansen et al., 2008; Sung et al., 2013, 2011; Wang et al., 2014), yet illuminate the importance of nighttime temperature as a potentially important driver of hospitalization. Due to the imperfect correlation between minimum temperature and other commonly used temperature metrics (such as mean and maximum temperature), previous studies may have underestimated the effect of temperature on mental health outcomes.

Unlike other studies of mental health disorders and atmospheric conditions, this research focused on a single disorder, and considered a more nuanced and climatologically informed approach to analyze the association between mental health and the atmosphere. Our study used a large sample size over nine years to build a robust sample population from the same climatological location. Similar to Wang et al. (2014), Sung et al. (2013, 2011), Lee et al. (2002), and Hansen et al. (2008) I found increased relative risk for hospitalization for mental and behavioral disorders (in our case, schizophrenia) under warmer conditions. Unlike other studies, our results did not examine the data through seasonally sub-setting of hospitalizations (Aviv et al., 2011; Shiloh et al., 2005) or heatwave scenarios (Wang et al., 2014). Our analysis also did not address potential impacts of solar radiation, unlike those from Brazil (Volpe and Del Porto, 2006), due to high correlation between all temperature variables and solar radiation.

We found that schizophrenia hospitalizations are more strongly associated with minimum temperature than maximum temperature. This difference is important as urban climate research has found that the urban heat island phenomena (warmer urban cores than surrounding rural regions) has the most pronounced signal in overnight temperature (Oke, 1973; Oke et al., 2017). Thus, urbanization may be indirectly connected to mental health issues through its causation of higher overnight temperature. While examination of heat mortality/morbidity most often uses daily mean or maximum temperature, this research points to the importance examining the influence of temperature observation time as a determinant of outcomes to help think through the causal processes/mechanisms (Robert E Davis et al., 2016). Under global climate change, temperature are expected to increase and urban areas are expected to see larger increases than global averages, particularly at night (Revi et al., 2014). Thus, I hypothesize the ~2% attributable risk will increase in the future in the absence of effective adaptation and mitigation strategies.

This study focused exclusively on schizophrenia-related hospitalizations in Maricopa County, Arizona, and should not be interpreted as representative beyond that outcome or setting. Additional single- and multi-site studies, and meta-analyses thereof, are necessary to provide a more global perspective on temperature-schizophrenia associations. Yet, the specific climate and context of the site matters. Specifically, nighttime temperature in urban areas are a significant factor in warming which can guide the policy and urban design discussions to better address the interactions between the environment and behavioral health. Additionally, I only considered schizophrenia-related ICD codes for this study. Others have looked more broadly at a range of mental and behavioral disorders that neurologically have a similar impact on the brain (Wang et al., 2014), yet with the large sample size I obtained with just schizophrenia, I wanted to reduce potential errors in the data due to over or mis-diagnosis (which are more common with other mental and behavioral disorders). Our analysis for sub-groups of the hospitalization record based on age, gender, and ethnicity was likely underpowered given the modest overall association between temperature and schizophrenia hospitalizations. Inclusion of a broader set of mental health outcomes (similar to Wang et al., 2014) may have revealed differences in outcomes for certain groups.

Additionally, I considered incorporating multiple atmospheric variables into our model; but given the high correlation between high minimum and high maximum temperature, I elected not to combine the two into a multi-variate DLNM that could tease out the relative impacts of the two. Confounding variables is a significant problem with using temperature and several atmospheric variables in Phoenix, such as solar radiation and relative humidity (Robert E Davis et al., 2016; Robert E. Davis et al., 2016).

Future examinations of mental health in Phoenix would benefit from an examination of other mental and behavioral disorders as well as exploring the possibility of temperature-mental health morbidity associations are evolving over time. Future work should also consider the relative impacts of the different causal pathways between extreme heat vulnerability and schizophrenia. I did not examine the impact of medication on relative risk and is an important factor to be examined.

While I examined temperature as the key independent variable driving associations with hospitalizations at short time scales (days), there are other environmental influences on community mental wellbeing that could be responsible for driving longer-term trends. Early planners and city designers sought to incorporate spaces and designs that used the natural landscape in the midst of their urbanizing structures and cities to foster better living conditions (Eisenman, 2013; Howard, 1898). These efforts had no scientifically proven connection between the two; yet, the connection was intrinsic within the work of designers such as Frederick Olmsted and Ebenezer Howard (Eisenman, 2016, 2013; Frumkin, 2003; Maller et al., 2006; Thompson, 2011). In the latter half of the 20th century, psychologists and sociologists began to see psychological disorders as having an undetermined connection with urban areas. Research examining the relationship between urban life and mental disorders, specifically schizophrenia found there to be a positive correlation (Lewis, 1992). Work in Europe found that mental disorders such as bipolar, manic depressive, and schizophrenia had a higher incidence in urban areas, even when incorporating the increased population and density (Vassos et al., 2016). While the exact nature relationship (causation or simply correlation between urbanization and schizophrenia) is still under investigation (March et al., 2008), the fact remains that in urban areas the relative incidence of schizophrenia increases. This is of note as the world continues to urbanize and urban areas are also connected with negative environmental impacts (such as poorer air quality and higher air temperature).

High daily minimum and maximum temperature in cities can be offset to some degree by a variety of heat mitigation strategies. One approach is to add vegetation in urban areas. The cooling impact of vegetation for green spaces in cities relative to their urbanized surroundings) (Bowler et al., 2010) is on the same order of magnitude of projected future heating (1-3 °C, mean temperature rise relative to 2010s) (Revi et al., 2014). Furthermore, Georgescu et al. (2014) looked at the broader impact on cities from urban climate mitigation strategies and found city-wide implementation of green roofs or green space can cool the city 0.5-1 °C compared to 2000 climatic norms. Additionally, by using vegetation to cool, city planners can also leverage non-thermal benefits of vegetation that epidemiologists, psychologists, and sociologists have found. These benefits include reduced physiological stressors (e.g. air pollution, urban heating) and psychological stressors (e.g., urban heating, noise and light pollution) (Frumkin, 2003; Kuo and Sullivan, 2001; Santamouris et al., 2018; Taylor et al., 2001). Urbanization and heat have a variety of negative outcomes for human health. Physiologically, humans are at higher risk of heat stress/stroke, respiratory problems and experience decreased thermal comfort (Gosling et al., 2009; Guo et al., 2017; Uejio et al., 2011).

Psychologically, humans may experience increased aggression, irritability, depression, and schizophrenia episodes (Anderson, 1989; Kuo and Sullivan, 2001; Lewis, 1992; March et al., 2008; Pedersen, 2015; Taylor et al., 2001). These effects are present, despite the fact that the most individuals spending an overwhelming majority of their time indoors (Klepeis et al., 2001). Conversely, contact or interaction with nature/vegetation can provide health benefits to the human population. These benefits include more physical activity, enhanced physical recovery and lowered blood pressure physiologically (Barton and Pretty, 2010; Ulrich, 1984; Ulrich et al., 1991).

Humans also benefit through improved self-esteem, enhanced positive mood, decreased anxiety, and reduced intensity of mental disorders (Barton and Pretty, 2010; Tzoulas et al., 2007). Yet, the type of cooling introduced by vegetative interventions may not be the most effective at decreasing the minimum temperature. Though I noted an impact from extreme maximum temperature, I noted that the relationship was slightly stronger for minimum temperature. As such, vegetation may not provide as effective nighttime cooling as other forms of shade might due to the evaporative cooling process (Coutts et al., 2016; S. H. Lee et al., 2016).

Taking steps to address the environmental impacts on risk for schizophrenia may also lead to a reduction in associated healthcare costs (Frumkin, 2003; Maller et al., 2006; Stensland et al., 2012). The theorized relationship between our individual mental wellbeing and the environment, specifically the causal pathway between schizophrenia and extreme heat (Fig. 1) is supported by the results of this study. I also see that this causal pathway has many potential intervention points. Yet, without intervention, our results show that extreme nighttime temperatures are more likely to exacerbate mental health concerns for those with schizophrenia than maximum temperature.

In conclusion, urban physical and mental health are affected by the ambient outdoor environment. Extreme heat is attributable to ~2.87% of the schizophrenia hospitalizations in the Phoenix metropolitan area. There was an additional burden to healthcare of $3.27 million over the study period in the Phoenix metropolitan area. While both measures of temperature were shown to have an effect on hospitalization, minimum temperature was found to be slightly more significant and there were no apparent differences among subgroups. This approach can be used to address the causal pathways to and from schizophrenia and extreme heat vulnerability, improving the community resilience in light of a warming and urbanizing world.

CHAPTER 5

CONCLUSION

5.1 Broad results of this research

The research set forth in this dissertation sought to examine the effect the built environment has on the thermal environment as well as consider ways in which the built environment can be modified to provide for the physical and psychological health of the community. Using the approach to urban design laid out by Ebenezer Howard and Frederick Law Olmsted, this research centered on the impacts cooling grey and green infrastructure might have on the community. This research considered the impacts to the thermal environment separate from the impacts on community wellbeing and mental health.

The city of Phoenix's redevelopment plans for Edison Eastlake provided a compelling case study into the potential effects of increasing tree canopy, building density, and green space on the thermal environment. To examine this, Chapter 2 dealt with the validation of a numerical model to appropriately represent the current neighborhood. The results discussed in Chapter 2 indicate the importance of the whole built environment system to the thermal environment. Strong air temperature validation using fixed weather stations provides confidence in the model's ability to predict the neighborhood's thermal environment. Yet, ENVI-met struggled to validate other atmospheric variables and I found a limitation of traverse measurement methodologies. This paper provides the methodological foundation to consider what impacts a redesign would have on the thermal environment of Edison Eastlake.

Chapter 3 took the design plans of the city and simulated the redevelopment under the same conditions as the model in Chapter 2. Chapter 3's results also show a modest benefit to the thermal environment by increasing the cooling grey and green infrastructure in the neighborhood. The redevelopment's ability to provide even 0.5-1 °C cooling at midday can have significant impacts when the summer afternoons are routinely hotter than has been experienced before (see summer of 2020). These two chapters address the questions around what the thermal environment is of a neighborhood and how effective is the city's design at mitigating the thermal environment through cooling grey and green infrastructure.

Chapter 4 discusses the impact the built environment and thermal environment of Maricopa County have on community mental wellbeing, specifically via schizophrenia. By examining hospitalizations in Maricopa County for schizophrenia, the mental health landscape for the city can be visualized. Results from Chapter 4 show an increased risk of hospitalization at higher temperatures generally, but most noticeably when minimum temperatures increase above 30 °C. This risk resulted in nearly $30 million in healthcare costs over 2006-2014 (using 2006 USD values). In 2020 dollars, that translates to over $37 million in cost burden on the Maricopa County healthcare system, insurance, and individuals. Currently, Phoenix sits on the cusp of this threshold during a large portion of the summer (again, see summer 2020). Future climate projections point this threshold being surpassed. Therefore, urban heat mitigation strategies using the built environment can extend beyond the physical health or the energy usage of the community, but also reach to aid in supporting the community mental wellbeing as well. However, increased tree canopy may not the most appropriate intervention for direct impacts on mental health, though other research suggests its value to community mental wellbeing in other forms (Frumkin, 2003; Maller et al., 2006).

In each chapter, the built environment's impacts on the thermal environment is considered and discussed using Howard and Olmsted's framework for viewing cooling grey and green infrastructure as an important factor to improving physical and mental health within the community (Eisenman, 2013; Howard, 1898). While Chapter 4 does not explicitly consider the influence cooling grey and green infrastructure may have on community mental wellbeing, there is research that upholds the value of green infrastructure for improving mental health. These concepts were hinted at in the 19th century by Howard and Olmsted, but only recently are there research analysis capabilities and knowledge to adequately assess the efficacy of their ideas on improving physical and psychological health of the community through cooling grey and green infrastructure.

Through this dissertation, we can see the potential benefits of cooling grey and green infrastructure for the communities that have discriminated against through implicit and explicit acts of environmental racism. By positioning these interventions in communities that have long been under-served, the city can begin to improve the environmental quality of the entire city through steps to address environmental and thermal equity. This can be used to design a future in Phoenix that is greener, cooler (relative to the nearby suburban and rural communities). Interventions, when ethically and culturally contextually designed, can be an effective strategy in creating healthy urban environments for all. This dissertation has sought to show that by integrating green infrastructure with urban design, hot neighborhoods can become physical and psychological oases, creating garden cities for tomorrow.

5.2 Implications/future research for the community and for academics

The value of this kind of research continues to remain apparent to many in Phoenix, particularly in 2020. However, the research itself is applicable beyond Phoenix. Recognizing and quantifying the thermal benefits to the community of a redeveloped neighborhood (particularly one of similar socio-economic levels as Edison Eastlake) is key to support community-informed, culturally contextual designs in city planning.

Additionally, the understanding of how our thermal environment is connected to community and hospital healthcare burdens is necessary as heat-related health concerns are nearly fully preventable (Guardaro et al., 2019). The burden from schizophrenia hospitalization is significant and the community, harnessed with this knowledge, can better pursue plans, policies, and procedures that can serve a portion of the population that are in desperate need of relief from the heat (particularly at night).

For the academic pursuit of knowledge, this dissertation points out the continued need for more information, clarity, and transparency by researchers as they utilize ENVI-met and other micro-climate models to assess building design, tree canopy, and atmospheric hazards induced by urban climate. Without proper validation, researchers may over-estimate the effectiveness of an intervention strategy. As such, this dissertation sets itself apart as one that is transparent about the flaws and limitations in the numerical modeling, the ways in which in situ measurement validation can be done (as well as guidance on best practices, or worse practices), and the components of the model that are highly sensitive to having accurate data inputs. Additionally, the statistical analysis performed on hospital data accounts for key influences in the data such as seasonality, holidays, and the lagged effects of the independent variables on hospitalization. Using this approach, the analysis was able to identify specific atmospheric variables that are more influential than others while also accounting for demographic differences among the dependent data.

5.3 Restatement of the problem and objective statements

Understanding the built environment's impacts on the thermal environment and subsequent psychological health is essential to assessing the efficacy of targeted urban heat mitigation strategies for cooling the urban population. Using the Edison Eastlake neighborhood in Phoenix, AZ and its planned redevelopment as a case study, this dissertation included three core elements: (1) a measurement campaign that included construction of weather stations in Edison Eastlake to validate numerical modeling of the neighborhood, (2) a heat mitigation analysis of the city's redevelopment plan that included increased building density, tree canopy, and green space; and (3) an examination of hospitalizations due to schizophrenia in Phoenix as a function of the thermal environment and implications of heat mitigation strategies on future mental wellbeing.

Chapter 2 assessed the validity of the numerical modeling (ENVI-met) via data collected through the measurement campaign. The validation used data from June 19, 2019 to assess ENVI-met's ability to represent the thermal environment neighborhood as it currently exists. Chapter 3 models the redevelopment plan in ENVI-met and examines the efficacy of this redevelopment for urban heat mitigation. The data are presented in relative terms rather than absolutes due to the limits of the validity of the baseline model from Chapter 2. Chapter 4 considers Maricopa County schizophrenia hospitalization from 2006 to 2014 and its relationship to the thermal environment. The analysis also includes a conversion from number of cases to the financial burden schizophrenia has on the healthcare system and assigns a percentage of cases and cost to hot nights, moderate nights, and cool nights.

5.4 Chapter 2 Conclusions

The ENVI-met model validation requires in situ measurements at fixed points as well as traverse measurements at key points in the year to validate the efficacy of the model for assessing the current thermal environment of the neighborhood. Thus, using these in situ measurements, I compared our ENVI-met model of Edison Eastlake to the data collected in the neighborhood. This was accomplished through GIS analysis of the model and the traverse measurements to compare each point location for the measured and modeled data. I also used receptor locations at the fixed weather station sites to analyze the diurnal profile at multiple locations within the domain.

For the June 2019 simulation, I find that the model does a sufficient job of estimating the intra-domain variability in air temperature using fixed weather stations. For air temperature at fixed weather stations, the RMSE had a range of 0.6 – 1.6 °C, and a Wilmott's index of agreement (*d*) range of 0.91-0.99. The rooftop fixed stations performed most poorly among the fixed weather stations. ENVI-met also struggled to accurately predict relative humidity and T_{MRT}. The model also could validate using mobile traverse measurements. While there are issues with the validation to mobile data, the ability of the model to correctly predict fixed intra-domain variability in the domain gives credibility to the model's prediction of the thermal environment.

Future work can build from this effort to deeply consider the parameterizations of the model and the effects of those parameterizations on the prediction of the thermal environment. Some issues in the model remain, including inflexible input parameters for wind speed, direction, and soil moisture. Despite these model issues, the rigorous validation of the model using multiple in situ data points to assess the model's ability to predict provide a sufficient foundation for the trustworthiness of the mode. Once calibrated and validated for the specific location and climate ENVI-met can be used for estimation of thermal impacts of various targeted heat mitigation strategies with the caveat and limitation of considering the relative impact of the redevelopment and rather than in absolute terms.

5.5 Chapter 3 Conclusions

Redesigning the neighborhood has an effect on the thermal environment of the neighborhood. The impact on the thermal environment is of particular interest as providing cooling benefits to the neighborhood was among the city's intended goals. Using the numerical model simulation validated in chapter 2, I re-simulated the neighborhood using the city's architectural designs for the redevelopment of Edison Eastlake. When comparing the two domains, I find that the rearrangement and rebuilding of the units, along with the increase in vegetation throughout the neighborhood (especially in a vegetated corridor along the western edge of the current Frank Luke units) has a cooling effect on air temperature of 0.5-1.5 °C at midday.

When considering the thermal comfort metric of mean radiant temperature, I find an average cooling effect of .1-.2 °C on the domain over the course of the day. Pockets of the domain provide locations of greater cooling than this average and some pockets that are warmer. This indicates that the shading from roofs, taller buildings, and the increase in tree canopy have net shading (and subsequent) cooling effect on the neighborhood. Yet, the warming locations can indicate locations that would most significantly benefit from added shade interventions as the redevelopment continues forward. The thermal environment of the community can be improved through this redesign as well as identifying areas for further improvement. The T_{MRT} cooling is best in the early morning and late afternoon, with a daytime minimum at noon.

These cooling benefits from the redevelopment are crucial in supporting the community. The community expressed a desire to have a cooler neighborhood as well as more green space. The city's plans include those physical features and the numerical modeling indicates some modest benefits to the neighborhood in the form of cooling the thermal environment. While the results are modest, modeling improvements and adjustments likely will increase the air temperature differences between the baseline design and the planned redesign. This means that the city is able to provide cooling through the design of its neighborhoods to all sectors of the city. The thermal inequity that is currently pervasive in this community can be reduced through cooling grey and green infrastructure changes.

5.6 Chapter 4 Conclusions

Health researchers have examined the physiological impacts of extreme heat on the human body. Yet, the mental health impacts of temperature have been understudied. A circular causal pathway connects schizophrenia and extreme heat: the environment can create circumstances that exacerbate mental health issues and mental health disorders can lead to increased susceptibility to extreme heat. Given the theoretical relationship between heat and mental health, I measured the association of temperature and schizophrenia hospital admissions in an arid urban climate and quantify the associated public health burden. I collected 80,000+ hospitalization records for schizophrenia from 2006-2014 in Maricopa County, Arizona, USA.

Using a distributed lag non-linear model (DLNM), I tested for a statistical association between temperature and schizophrenia hospital admissions after controlling for year, season, and holidays. I subsequently calculated the cumulative attributable risk of high temperature on schizophrenia. The relative risk of schizophrenia hospital admissions increased with high temperature. Statistical models using daily minimum temperature were better fits to the data than those using daily mean or maximum. Schizophrenia hospital admissions notably increased on days with minimum temperature above 30 °C. I estimated the total fraction of schizophrenia hospital admissions attributable to hot minimum temperature as 2.87% (CI: -2.05-6.85%). Although there did not appear to be a significant difference by age or ethnicity, I found that females are at a slightly increased risk relative to males. High and low minimum temperatures impose a substantial mental health burden on the population of Maricopa County, Arizona. A conservative estimate of healthcare costs annually from temperature-induced schizophrenia hospitalization is over $3 million USD. Therefore, focusing on nighttime cooling may be beneficial to improve community resiliency in mental health.

As the city experiences more and more summers where the minimum temperature hover or exceed the identified threshold of 30 °C, the need for more resources will rise unless steps are taken to mitigate exposure to the heat for this population. One such step could be through the cooling grey and green infrastructure that Chapters 2 and 3 indicate may be viable way to cool city neighborhoods.

5.7 Limitations to the research

Overall, many of the limitations to the research were related to ENVI-met and modeling in general. Due to the computationally expensive nature of ENVI-met, only one redesign implemented due to model simulation time. Data are available to run a similar model for an October day to give some analysis for the seasonal impacts of the redevelopment. In addition to being computational expensive, ENVI-met is a "black box". There are a lot of defaults and settings within ENVI-met that hidden behind the GUI and without more transparency about the assumptions, it is difficult to assess the source of errors or issues with model.

While previous research has suggested that a few hours of spin up is sufficient, further examination would be beneficial. Simulating beyond 24 hours creates many issues in ENVI-met as there is no mechanism for water to be introduced into the model during the simulation. As such, the soil dries out too quickly and as the simulation moves beyond day 1, the domain becomes drier and warmer than reality.

Another limitation surrounding the soil moisture is how dry the model must be in a hot and arid climate. Under such extreme conditions, the soil rapidly heats up during the day, even with the presence of vegetation. Soil moisture typically is higher with vegetation and subsequently, the surface remains cooler and there is more evapotranspiration occurring that results in cooler air temperature. The model's configuration currently prevents a non-uniform application of soil moisture that would better represent the heterogeneity of the urban land cover and provide a more accurate depiction of its impacts on the thermal environment.

The schizophrenia research was limited to Maricopa County hospitalization data from 2006-2014. The data did not allow for deeper trend analysis to understand the relative risk for subsets of the population. Future research should work to expand years, examine other mental health disorders, as well as look to add in more regions to this study create a more latitudinal approach to this line of research.

5.8 Resulting publications

Below is a list of peer-reviewed and grey literature publications that were published or went into review prior to the defense of this dissertation.

Crank, P.J.; Middel, A.; Wagner, M.; Hoots, D.; Smith, M.; Brazel, A. (2020). Validation of Seasonal Mean Radiant Temperature Simulations in Hot Arid Tempe, Arizona. Science of the Total Environment. https://doi.org/10.1016/j.scitotenv.2020.141392 **(related to Chapter 2)**

Using Kestrel Heat Stress Trackers and MaRTy, I validated ENVI-met and Rayman for Mean Radiant Temperature (T_{MRT}) across seasons. This sensitivity analysis included cold and extremely hot conditions. The validation used downtown Tempe as the case study to assess performance in a complex urban area with a hot, arid climate. Both models struggled to consistently model T_{MRT} across the seasons. RayMan struggled with complex urban form and enclosed spaces. ENVI-met's inability to resolve the intra-domain spatial variability that prevalent with T_{MRT} and with engineered shade. Hot conditions were problematic for both models. T_{MRT} was underestimated in winter and shoulder seasons and overestimated in the summer. Results point to the critical importance of in situ validation to assess directional bias (under/over-estimation) and quantify errors.

Messerschmidt, M.; Grimm, N.; Hondula, D. M.; Feagan, M.; Beute, S.; Berisha, V.; White, J.; Guardaro, M.; Perea, M.; Ramirez, M.; Olivas, E.; Bueno, J.; Crummey, D; Winkle, R.; Rothballer, K.; Mocine-McQueen, J.; Maurer, M.; Coseo, P.; Crank, P. J.; McCauley, L. (2019). Heat Action Planning Guide for Neighborhoods of Greater Phoenix: Creating Urban Heat Solutions in the Valley of the Sun. The Nature Conservancy. **(related to chapter 3)**

In this report, I walk through the impacts of urban heat on the health, safety, and economy of the Greater Phoenix region. Beginning in May 2017, The Nature Conservancy, Maricopa County Department of Public Health, Central Arizona Conservation Alliance, Urban Resilience to Extremes Sustainability Research Network, Arizona State University's Urban Climate Research Center, and Center for Whole Communities launched a participatory Heat Action Planning process in three neighborhoods in the Valley of the Sun. Community base organizations joined the project to support the participatory process that was designed to develop agency, awareness, and social cohesion in underrepresented communities. In addition, the project sought to serve as a model on how to create local, contextual, and culturally appropriate urban heat resilience strategies with the goal of a safer and healthier future. Working in an iterative format, the project combined leading scientific evidence and the wisdom found through storytelling to better understand the existing and probable future challenges of the residents and communities during extreme heat events. Residents brought forth their ideas on this and these ideas were then intentionally incorporated into design plans. Shade was a key feature to increasing thermal comfort by residents along with vegetation corridors. The result of this project highlights the importance of residents' experiences and increasing community agency in the neighborhood designs.

Crank, P. J.; Hondula, D. M.; Sailor, D. J. Mental Health and Heat: A Distributed Lagged Non-Linear Model Approach to Risk and Mitigation for Schizophrenia Hospitalization Admissions in Arid and Urban Climates Environmental Health Perspectives. Submitted (July 2020). **(related to Chapter 4)**

Extreme heat has been shown to have a negative impact on the human's ability to perform both physical and cognitive tasks. Heat additionally has been shown to affect the mental state of persons. Yet, research also points to the mental state of persons having an effect on the person's physical response to extreme heat. Thus, for mentally compromised individuals living in extreme thermal conditions, the relative risk for health concerns increases. Studying schizophrenia hospital admissions in Maricopa county, I find that heat (defined by daily minimum temperatures above 22 °C) is attributable for 2.87% (CI: -2.05-6.85%) of the schizophrenia hospitalizations in Phoenix between 2006 and 2014. The burden of these hospitalizations account for nearly $30 million in healthcare costs from 2006-2014 (using 2006 USD).

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APPENDIX A

TABLE OF EDISON EASTLAKE INSTRUMENT METADATA

Name	Instrument	Model	Range	Range/ Accuracy	Installation Date	Latitude	Longitude	Type	Notes
1-P	Temp/RH	U23	**Air Temperature** -40° to 70°C **Relative Humidity** 0-100% RH, -40° to 70°C	**Air Temperature** ±0.21°C from 0° to 50°C **Relative Humidity** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis at 25°C; below 10% and above 90% ±5% typical	2018-06-21; instrument swapped 2019-06-14	33.45274	-112.046	Pole	Instruments were swapped for new ones with fresh batteries on June 14, 2020
6-P	Temp/RH	U23	**Air Temperature** -40° to 70°C **Relative Humidity** 0-100% RH, -40° to 70°C	**Air Temperature** ±0.21°C from 0° to 50°C **Relative Humidity** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis at 25°C; below 10% and above 90% ±5% typical	2018-06-21; instrument swapped 2019-06-14	33.4542	-112.039	Pole	Instruments were swapped for new ones with fresh batteries on June 14, 2020
7-P	Temp/RH	U23	**Air Temperature** -40° to 70°C **Relative Humidity** 0-100% RH, -40° to 70°C	**Air Temperature** ±0.21°C from 0° to 50°C **Relative Humidity** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis at 25°C; below 10% and above 90% ±5% typical	2018-06-21; instrument swapped 2019-06-14	33.45486	-112.04	Pole	Instruments were swapped for new ones with fresh batteries on June 14, 2020
8-P	Temp/RH	U23	**Air Temperature** -40° to 70°C **Relative Humidity** 0-100% RH, -40° to 70°C	**Air Temperature** ±0.21°C from 0° to 50°C **Relative Humidity** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis at 25°C; below 10% and above 90% ±5% typical	2018-06-21; instrument swapped 2019-06-14	33.45554	-112.041	Pole	Instruments were swapped for new ones with fresh batteries on June 14, 2020

Name	Instrument	Model	Range	Range/ Accuracy	Installation Date	Latitude	Longitude	Type	Notes
Aeroterra	Data Logger	HOBO RX3000 Station - CELL-3G	--	--	2018-06-20	33.45544	-112.047	Roof	$15/month cellular data fee, fronted by UCRC. – *April 2020, fronted by CAP LTER* Battery not charging -- May 2020. Cleaned May 29, 2020 Battery replaced... TBD
Aeroterra	Temp/RH	S-THB	**Air Temperature** -40°C to 75 °C **Relative Humidity** 0-100%	**Air Temperature** ±0.2°C over 0° to 50°C **Relative Humidity** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5RH	2018-06-20	33.45544	-112.047	Roof	
Aeroterra	Anemometer	S-WSB	0 to 76 m/s	±1.1 m/sec or ±4% of reading, whichever is greater	2018-06-20	33.45544	-112.047	Roof	
Aeroterra	Wind Direction	S-WDA	0-335 °, 5 ° dead band	±5°	2018-06-20	33.45544	-112.047	Roof	
Aeroterra	Pyranometer	S-LIB	0 to 1280 Wm^{-2};	Typically within ±10 Wm^{-2} or ±5%, whichever is greater in sunlight; Additional temperature induced error ±0.38 Wm^{-2}/°C from 25°C	2018-06-20	33.45544	-112.047	Roof	Replaced after malfunctioning August 2018 Malfunctioning since summer 2019

Name	Instrument	Model	Range	Range/ Accuracy	Installation Date	Latitude	Longitude	Type	Notes
Aeroterra	Data Logger	HOBO RX3000 Station - CELL-3G	--	--	2018-06-20	33.45544	-112.047	Roof	$15/month cellular data fee, fronted by UCRC. – *April 2020, fronted by CAP LTER* Battery not charging -- May 2020. Cleaned May 29, 2020 Battery replaced… TBD
Aeroterra	Temp/RH	S-THB	**Air Temperature** -40°C to 75 °C **Relative Humidity** 0-100%	**Air Temperature** ±0.2°C over 0° to 50°C **Relative Humidity** ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5RH	2018-06-20	33.45544	-112.047	Roof	
Aeroterra	Anemometer	S-WSB	0 to 76 m/s	±1.1 m/sec or ±4% of reading, whichever is greater	2018-06-20	33.45544	-112.047	Roof	
Aeroterra	Wind Direction	S-WDA	0-335 °, 5 ° dead band	±5°	2018-06-20	33.45544	-112.047	Roof	
Aeroterra	Pyranometer	S-LIB	0 to 1280 Wm^{-2};	Typically within ±10 Wm^{-2} or ±5%, whichever is greater in sunlight; Additional temperature induced error ±0.38 $Wm^{-2}/°C$ from 25°C	2018-06-20	33.45544	-112.047	Roof	Replaced after malfunctioning August 2018 Malfunctioning since summer 2019

Name	Instrument	Model	Range	Range/ Accuracy	Installation Date	Latitude	Longitude	Type	Notes
MaRTy 2.0	Data Logger	CS			Traverse Schedule	Traverse Map	Traverse Map	Cart	
MaRTy 2.0	Temp/RH	HC2S3 Rotronic HygroClip2 T/RH Probe	**Air temperature** -50 to 100 °C **Relative Humidity** 0 to 100%	**Air temperature** ±0.1 °C **Relative Humidity** ±0.8 RH	Traverse Schedule	Traverse Map	Traverse Map	Cart	
MaRTy 2.0	Wind Speed	Gill 2D WindSonic	0 to 60 ms^{-1}	±2% @ 12 ms^{-1}	Traverse Schedule	Traverse Map	Traverse Map	Cart	
MaRTy 2.0	Lat/Lon	GPS 16X Garmin GPS	-90 to 90° -180 to 180°	Less than 3 m	Traverse Schedule	Traverse Map	Traverse Map	Cart	
MaRTy 2.0	SW/LW Radiation	3 Hukseflux 4-Component Net Radiometers	**SW** 285 to 3000 x 10^{-9} m **LW** 4.5 to 40 x 10^{-6} m	**SW** ±10% **LW** ±10%	Traverse Schedule	Traverse Map	Traverse Map	Cart	