Microscale Modeling Of The Canopy-Layer Urban Heat Island In Phoenix, Arizona: Validation And Sustainable Mitigation Scenarios

by

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ABSTRACT

Metropolitan Phoenix, Arizona, is one of the most rapidly urbanizing areas in the U.S., which has resulted in an urban heat island (UHI) of substantial size and intensity. Several detrimental biophysical and social impacts arising from the large UHI has posed, and continues to pose, a challenge to stakeholders actively engaging in discussion and policy formulation for a sustainable desert city. There is a need to mitigate some of its detrimental effects through sustainable methods, such as through the application of low-water, desert-adapted low-water use trees within residential yards (i.e. urban xeriscaping). This has the potential to sustainably reduce urban temperatures and outdoor thermal discomfort in Phoenix, but evaluating its effectiveness has not been widely researched in this city or elsewhere.

Hence, this dissertation first evaluated peer-reviewed literature on UHI research within metropolitan Phoenix and discerned several major themes and factors that drove existing research trajectories. Subsequently, the nocturnal cooling influence of an urban green-space was examined through direct observations and simulations from a microscale climate model (ENVI-Met 3.1) with an improved vegetation parameterization scheme. A distinct park cool island (PCI) of 0.7-3.6 °C was documented from traverse and model data with larger magnitudes closer to the surface. A key factor in the spatial expansion of PCI was advection of cooler air towards adjacent urban surfaces, especially at 0-1 m heights. Modeled results also possessed varying but reasonable accuracy in simulating temperature data, although some systematic errors remained.

Finally, ENVI-Met generated xeriscaping scenarios in two residential areas with different surface vegetation cover (mesic vs. xeric), and examined resulting impacts on near-surface temperatures and outdoor thermal comfort. Desert-adapted low-water use shade trees may have strong UHI mitigation potential in xeric residential areas, with greater cooling occurring at (i.) microscales (~2.5 °C) vs. local-scales (~1.1 °C), and during (ii.) nocturnal (0500 h) vs. daytime periods (1700 h) under high xeriscaping scenarios. Conversely, net warming from increased xeriscaping occurred over mesic residential neighborhoods over all spatial scales and temporal periods. These varying results therefore must be considered by stakeholders when considering residential xeriscaping as a UHI mitigation method.

To Tze Wei and Alicia:

For teaching me what life really is

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"*Nanos gigantium humeris insidentes*" - Bernard of Chartres.

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CHAPTER 1: INTRODUCTION

1.1: The urban heat island

"But the temperature of the *city* is not to be considered as that of the *climate*; it partakes too much of an artificial warmth, induced by its structure, by a crowded population, and the consumption of great quantities of fuel in fires: as will appear by what follows." (Howard 1833, 3)

The study of the urban heat island (UHI) has substantially developed since Luke Howard first observed that London was distinctly warmer than its rural environs. Decades of observational and modeling studies have shown that the UHI is ubiquitous in cities of all climate types, and have greatly expanded on Howard's original treatise. We currently know that there are several different and distinct UHI sub-types; sub-surface, surface, canopy-layer and boundary-layer (Oke 1995). Observation of each sub-type has distinct methodologies, ranging from stationary point measurements or mobile traverses (canopy-layer), remote sensed platforms and infra-red thermometers (surface and sub-surface), and through radiosonde data (boundary-layer). Following from Howard's initial speculations, detailed examination of factors that (i.) cause each UHI sub-type, and (ii.) modify its form and magnitude have also occurred (Oke 1987); although the relative importance of each factor through modeling attribution varies for each city and sub-type (Grimmond et al. 2010). Research into the influence of UHI on humans, flora and other fauna, as well as on approaches and methods to mitigate its detrimental impacts subsequently developed from its physical study (Yow 2007). However, these research avenues, together with implementation of either adaptation and mitigation policies related to UHI, have not been as widely studied compared to its physical form (Oke 2006b).

UHI research in Phoenix, Arizona, is comparatively more developed in both quantity (i.e. number of peer-reviewed journal studies) and quality (i.e. covering differing research trajectories) when evaluated with other arid desert or subtropical cities (Roth 2007; Brazel and Heisler 2009). There has been notable research within the city of its physical basis, both in the observation and modeling of various UHI types across different spatial scales; all of which have been important contributions to subtropical and desert UHI knowledge. Phoenix UHI research has also been significant in advancing scientific understanding and knowledge of UHI impacts on biological and socio-economic domains, and this has also provided some insight into understanding the utility of several UHI mitigation methods for a desert city.

Despite this remarkable body of knowledge relative to other cities, some notable gaps remain with respect to modeling micro- and local-scale UHI in the residential suburbs of Phoenix, and subsequent modeling of its potential mitigation. This echoes the dearth of research into the latter point within other cities, of which calls for more applied studies into this aspect have been made by prominent urban climatologists (e.g. Oke 2006b). Recent research in Phoenix utilized statistical models derived from climate data obtained from other cities to examine potential mitigation at crude spatial scales without accounting for temporal variations of dynamic near-surface climate processes (e.g. Gober et al. 2010); or have applied numerical physics-based microscale (i.e. typically between

1-100 m^2) and local-scale (~1 km^2) models only in downtown Phoenix without accurate parameterization of initial climate, urban surfaces or local vegetation (e.g. Emmanuel and Fernando 2007). There is still uncertainty regarding the potential of reducing urban warmth at microscales in this city over different residential surface types, especially with the application of modeling approaches that would be useful for stakeholders interested in sustainable application of effective UHI mitigation methods.

Thus, this dissertation primarily examines the microscale near-surface UHI (i.e. within the urban canopy layer) in Phoenix through the ENVI-Met microscale urban climate model (Bruse and Fleer 1998; Bruse 2010). A significant part of this research involved evaluating the model with observed temperatures at fine spatial resolutions, as well as on improving default model vegetation parameterization schemes. Subsequently, several sustainable UHI mitigation scenarios (i.e. with the use of low-water consumption, broad canopy shade trees) were tested with ENVI-Met for selected residential areas. The effectiveness in reducing urban warmth and improving outdoor thermal comfort over different spatial (micro- vs. local-) and temporal (daytime vs. nocturnal) scales was also evaluated. The comparison of fine vs. course spatial impacts could be useful for several issues, such as the effectiveness of applied UHI mitigation, or for potentially evaluating model physics and performance with other models. This dissertation also includes a thorough review of the research literature on canopy-layer UHI research in Phoenix, with a strong focus on its theoretical contributions to knowledge about the UHI as well as towards sustainable urban climatology.

1.2: Dissertation format

There are a total of five chapters in this dissertation, with three major chapters each being a separate first-authored manuscript. These were submitted to peer-reviewed journals that frequently publish urban climate and UHI articles. In each article, I was responsible for originating the study's research questions and objectives, as well as (i.) deciding on primary methodology and data collection, (ii.) data analysis and subsequent discussion of results, (iii.) being the lead author in writing and formatting each manuscript for journal submission, and (iv.) responding to referee and editorial comments during peer-review. Each chapter also explicitly describes the research objectives, questions and methods that are central to this dissertation.

The first article is a comprehensive literature review of canopy-layer UHI research within Metropolitan Phoenix. The objectives of this chapter were to discern generalized and distinct research themes and approaches for UHI research in Phoenix; to analyze results or significant theoretical contributions from Phoenix with respect to other cities in similar (or dissimilar) climates; and to examine the factors that motivated UHI research trajectories in the metropolitan area. This chapter was submitted to the *Bulletin of the American Meteorological Society* in January 2011.

The second article examines the observed and modeled temperatures observed within the ASU campus (through a bicycle traverse and the application of the ENVI-Met model) with the objective of evaluating the horizontal and vertical dimensions of the Park Cool Island (PCI), with the secondary objective of evaluating the accuracy of ENVI-Met temperatures within the local-scale study area. This chapter was submitted to *Theoretical and Applied Climatology* in 2009 and has since been published in January 2011.

Using the ENVI-Met model applied in the previous chapter, the third article models several UHI mitigation scenarios that utilize several low-water use, broad canopy shade trees in distinct residential areas in Phoenix (i.e. landscape conversion by "xeriscaping"). After evaluating model accuracy with observed temperature data from meteorological stations sited within the residential neighborhoods, the study documents and analyzes the potential cooling resulting from different xeriscaping scenarios, as well as contrasts the different spatial impacts at micro and local-scales over different times of day during an extreme heat event in Phoenix. This chapter was submitted to *Building and Environment* in February 2011.

A short concluding chapter summarizes the results obtained, and evaluates the contribution of this dissertation towards UHI research, both within Phoenix and in the field of urban climatology. Lastly, the appendix section includes a statement of permission for including the aforementioned manuscripts as chapters for this dissertation is included in the appendices.

CHAPTER 2: URBAN HEAT ISLAND RESEARCH IN PHOENIX, ARIZONA: THEORY, IMPACTS AND SUSTAINABLE MITIGATION[1]

2.1: Abstract

Over the past 60 years, metropolitan Phoenix, Arizona, has been among the fastest-growing urban areas in the U.S., and this rapid urbanization has resulted in an urban heat island (UHI) of substantial size and intensity. Several detrimental biophysical and social impacts arising from the large UHI has posed, and continues to pose, a challenge to citizens, scientists, planners and decision-makers actively engaging in discussion and policy formulation for a sustainable desert city. In this review, we evaluated peer-reviewed literature on UHI research within metropolitan Phoenix, and discerned three major themes across different spatial scales: (i.) theoretical contributions from documenting, modeling and analyzing the physical characteristics of the UHI, (ii.) inter-disciplinary investigation into its biophysical and social consequences, and (iii.) subsequent research into, and policy implementation of sustainable UHI mitigation and adaptation techniques. Several factors intrinsic to Phoenix facilitated much UHI research; a high-quality, long-standing network of urban meteorological stations allowing for relatively fine spatial resolution of near-surface temperature data; strong applied urban climate research partnerships between several agencies, such as the academy, the National Weather Service, private energy firms and municipal governments; and a high level of public and media interest towards the UHI. As UHI-related environmental problems are not unique to Phoenix, and are

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[1] This manuscript was co-authored with Anthony J. Brazel and was submitted to *Bulletin of the American Meteorological Society* in January 2011.

illustrative of problems in other rapidly expanding subtropical cities, the results and conclusions from this review can be a useful contribution towards the study of sustainable urban climates.

2.2: Introduction

The large desert city of Phoenix, Arizona, together with 26 adjacent municipalities and Native American communities, is the focal point of the expansive Phoenix Metropolitan Area (PMA) (~37 000 km^2) (Figure 1). Since 1950, the PMA experienced extensive land-use and land cover (LULC) alterations, changing from a predominantly agricultural region to a metropolis mostly comprised of residential suburbs (Figure 2). Consequently, several inter-related environmental concerns arose that potentially threatened its long-term sustainability, which include water scarcity (e.g. Wentz and Gober 2007), reduction of native biodiversity (e.g. Grimm et al. 2008), poor urban air quality (e.g. Doran et al. 2003, Lee et al. 2007), and the urban heat island (UHI).

The last feature is the phenomenon of warmer urban areas vis-à-vis pre-urban or "rural" surroundings. The UHI is caused by several factors that can be directly attributed to LULC change, such as alterations to the surface energy balance from increased absorption of radiation energy, higher anthropogenic heat emissions, and decreased surface evapotranspiration in urban areas (Oke 1982). Magnitudes of maximum UHI intensity, defined as the largest difference between urban and rural temperatures ($\Delta T_{u\text{-}r}$), are also influenced by synoptic weather type, morphology of the urban area, timing of temperature observations, and categorization of “rural” areas adjacent to the city (Chow and Roth 2006; Stewart 2010). At a global scale, the UHI is generally detrimental to the climate comfort of urban residents, and increases their vulnerability to heat stress especially when coupled with global temperature increases (e.g. Wilbanks et al. 2007).

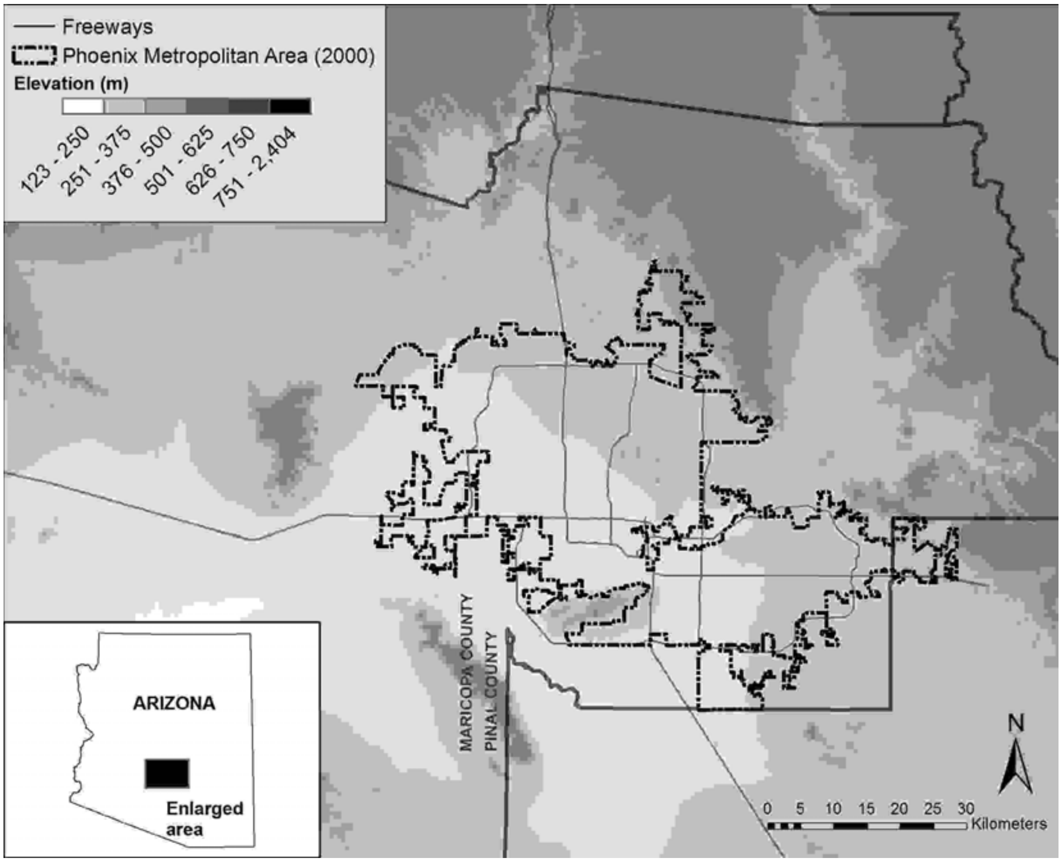

Figure 1: The boundaries of the Phoenix Metropolitan Area (PMA) in 2000 and surrounding topography. Note the higher elevations in the northern and eastern margins of the city.

Compared to other cities, there exists a large body of academic work on the Phoenix UHI that has examined its physical characteristics, impacts, and possible mitigation methods (Brazel and Heisler 2009). The broad extent of literature, however, raises several important questions: Are there generalized and discernable research themes and approaches for UHI research in Phoenix?

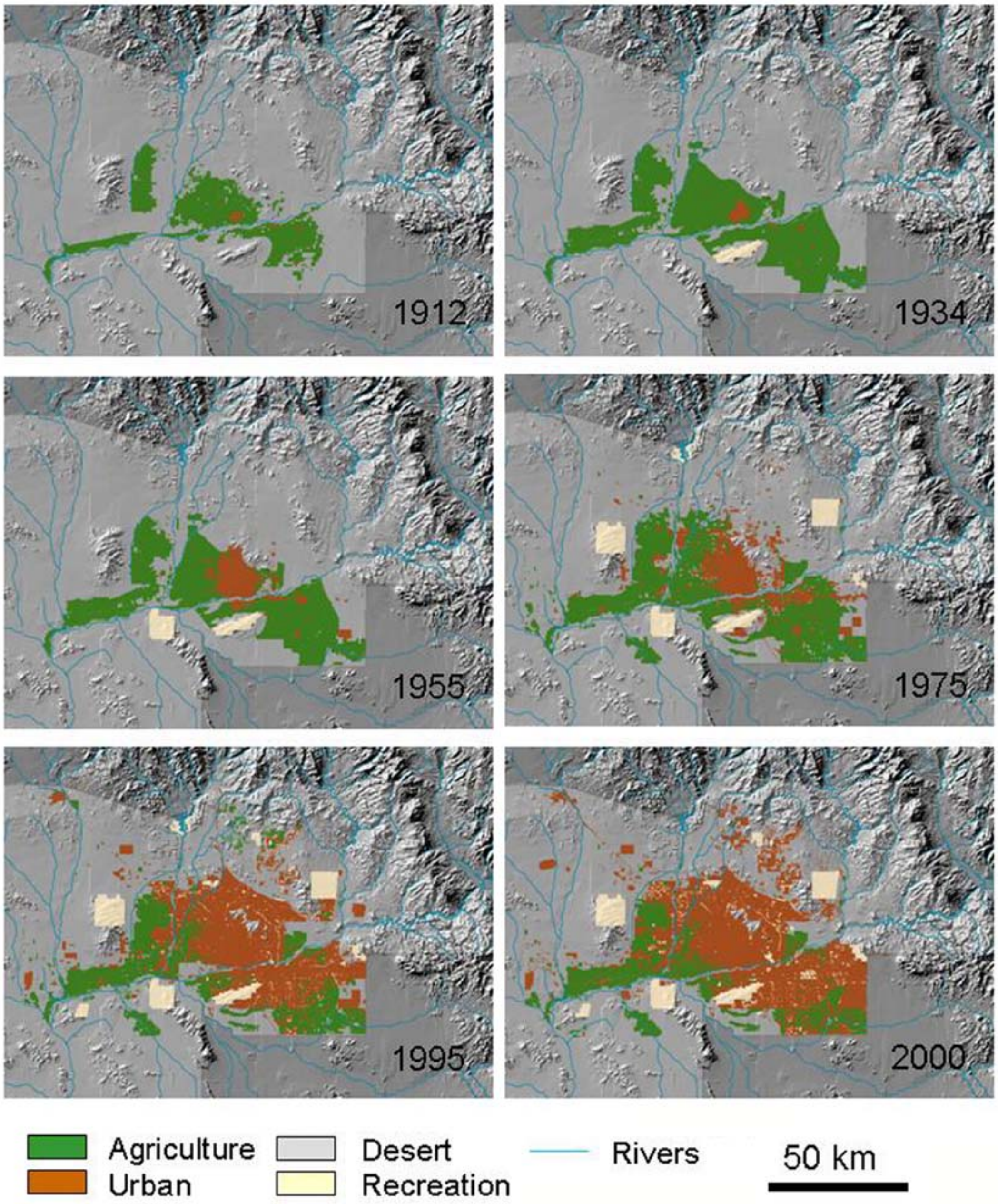

Figure 2: Land-use/land cover (LULC) change in the PMA from 1912-2000 illustrating the increase of urbanized land cover at the expense of desert and agricultural land-use (Source: Central Arizona – Phoenix Long-term Ecological Research (CAP-LTER)).

What findings or theoretical contributions have there been with respect to other cities in similar (or dissimilar) climates? What factors motivated the research trajectories for UHI study in Phoenix? As UHI-related environmental problems are not unique to Phoenix, a review of methods, results and conclusions from research hitherto would be a useful contribution to urban climatology and sustainability, especially if the accumulated knowledge can be applied to other subtropical desert cities.

Therefore, this article comprehensively reviews UHI research occurring within the PMA that are mostly based on peer-reviewed studies from 1921. We define UHI in this article as the difference between urban and rural near-surface temperatures (ΔT_{u-r}) measured at ~2 m above surface level (a.s.l.), which is within the urban canopy-layer (Oke 1976). Temperature differences here are of greatest relevance to urban residents compared to other UHI types (e.g. the surface heat island), and have been the focus of much research in the city[2].

2.3: UHI research in Phoenix

We identified three major research themes – each with several distinct approaches – which contributed to scientific knowledge about the Phoenix UHI over time (Figure 3). Most published studies initially defined, explained and modeled its physical characteristics via inductive epistemologies based on singular scientific disciplines. Results and conclusions from these studies were drivers of subsequent applied work that (i.) evaluated direct and secondary

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[2] Detailed study into surface ΔT_{u-r} in Phoenix also exists (e.g. Balling and Brazel 1989; Stoll and Brazel 1992; Jenerette et al. 2007; Golden et al. 2009; Buyantuyev and Wu 2010).

impacts of UHI on urban residents, and; (ii.) examined possible sustainable mitigation and adaptation methods. These latter studies also largely involved interdisciplinary methods arising from researchers that included social scientists and engineers. In due course, more studies gradually used deductive epistemologies that were based on prior generalizations and theory.

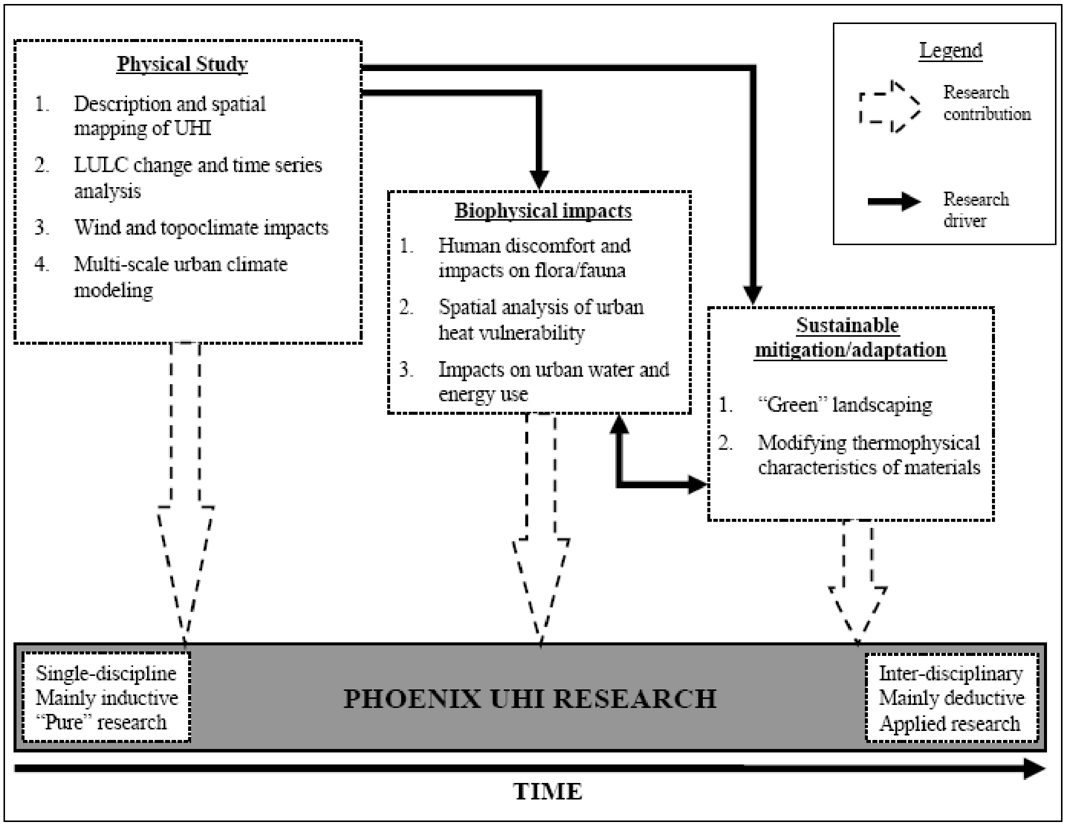

Figure 3: The chronological development of major UHI research themes and approaches (within dashed rectangle boxes) with their contributions to knowledge of the PMA UHI.

2.3.1: Physical characteristics of UHI – approaches

The first approach mostly described urban vs. rural temperature differences in mapping UHI form, via the interpolation of point (i.e.

meteorological station) data of maximum (T_{max}) or minimum (T_{min}) temperatures observed over summer or winter. For instance, Gordon (1921) reported a relatively small mean winter $\Delta T_{u\text{-}r}$ (~2.7 °C) based on station T_{min} data from 1913-1920 between the urban core of Phoenix and its surrounding agricultural and desert environs at similar elevations. By 1977, mean winter T_{min} UHI increased to 4 °C, and corresponded with eastward expansion of higher urban temperatures from suburban development (Hsu 1984). The historical expansion of UHI form with LULC change was also documented through statistical interpolation of summer T_{min} data (Balling and Brazel 1987; Brazel et al. 2007).

All these studies documented a distinct UHI, with higher temperatures over the urban core vs. outlying "rural" or non-urban areas. The form of the Phoenix UHI had "plateaus" of elevated temperatures within most suburban areas extending to the urban fringe, where new suburban housing completions were greatest. Further, a distinct "oasis effect" of lower urban core daytime temperatures was observed – a feature also observed in other desert cities (e.g. Givoni 1991) – likely caused by increased evapotranspiration from urban vegetation in a hot arid climate, combined with larger heat storage in urban areas. There was little discussion, however, on the accuracy of these "soft data" (i.e. uncertain, spatially interpolated temperature data based on exact measurements from meteorological stations) applied in these studies. Lee et al. (2008) examined this and found enhanced data accuracy in UHI interpolation via a Bayesian Maximum Entropy (BME) that accounts for spatio-temporal discontinuities in temperature data over other geostatistical methods (i.e. kriging).

Another approach utilized time-series analysis of mean T_{max} or T_{min} in examining meteorological station (or station network) temperature data over long (i.e. decadal) time-scales. Significant warming trends were evident during the latter half of the 20th century for stations sited in urban areas of the PMA which corresponded to the growth of the Phoenix UHI (Cayan and Douglas 1984; Hansen et al. 1999; Lee and Ho 2010; Svoma and Brazel 2010). Further 20th century time-series analysis of urban-rural differences in T_{max} and T_{min} showed that magnitudes of the daytime oasis effect did not vary significantly; T_{min} data, however, showed significant increasing trends of ΔT_{u-r}, peaking at ~5 °C between Phoenix and Sacaton (a "rural" site located ~25 km SE of the PMA) in 1995 (Brazel et al. 2000).

Several studies also examined the physical characteristics and dynamics of the Phoenix UHI at shorter (i.e. diurnal or seasonal) time-scales. These studies differ in method either by using vehicles equipped with fast-response temperature sensors that traverse across different land-use categories (e.g. Brazel and Johnson 1980; Stabler et al. 2005; Hedquist and Brazel 2006; Sun et al. 2009), or via stationary measurements from a network of temperature sensors located on different land surface types (e.g. Hawkins et al. 2004; Fast et al. 2005; Hedquist and Brazel 2006). Results indicated that (i.) UHI intensity is largest at night; (ii.) maximum ΔT_{u-r} generally occurs under clear and calm weather (i.e. anti-cyclonic) conditions generally observed during summer; (iii.) LULC categorizations are a significant factor in affecting ΔT_{u-r}, with magnitudes varying according to surface type; and (iv.) larger ΔT_{u-r} magnitudes are observed when the "rural" LULC is agricultural/grass as opposed to desert (Table 1). While results (i.-iii.) are similar to conclusions from UHI studies in other cities (e.g. Arnfield 2003), (iv.) is an important theoretical contribution in defining "rural" when examining ΔT_{u-r}. This is fundamental in underpinning all UHI research (Stewart and Oke 2009; Stewart 2010), and also illustrates the greater cooling potential of grass vs. desert surfaces in mitigating UHI.

Table 1: Summary of results, rural definitions and weather conditions obtained from short-term canopy-level UHI studies in Phoenix. Times are reported in local time (UTC -7 h).

Study	Time of study	Method/ Observation heights a.s.l.	Maximum ΔT_{u-r} /Time (h)	Defined "rural" area	Weather during max. ΔT_{u-r}
Brazel and Johnson (1980)	Mar and Jun 1975, 1976	Traverse/ 0.6, 5 m	~ 7 °C/ 0500	Agricultural field	"stable and clear"
Hawkins et al. (2004)	Apr 2002	Station/ 1.5 m	14.6 °C (a); 10.7 °C (b)/ 2100-2200	Grass (a); "Hardpan dirt" (b)	Wind speeds ~ 0.1 ms^{-1}; cloud cover unknown
Fast et al. (2005)	Jun-Aug 2001	Station/ ~3 m (rural, suburban), 20-110 m (downtown)	~10 °C /~2000	Bare ground/ agricultural	Unknown
Stabler et al. (2005)	Jun and Dec 1999	Traverse/ 2 m	8.5 °C/ 0500-0600	Agricultural field	Clear and calm , anti-cyclonic synoptic conditions
Hedquist and Brazel (2006)	Jul-Dec 2001	Traverse and station/~2 m	7.32 °C/ 2100-2200	Agricultural field	Unknown
Sun et al. (2009)	Nov 2007	Traverse/ ~1.5 m	8.2 °C/ 2300-0100	Agricultural field	Mostly cloudless; ~5 ms^{-1}

Another approach examines how the complex topography of the PMA influences UHI form and dynamics. The city lies within a large, gently-sloping valley floor orientated in a generally E-W axis, with mountainous areas to the N and E. Valley floor elevations range from ~290 m (west) to 515 m (east) (Figure 1). The edges of the northern and eastern valley floor are also marked by several mountain ranges of high topographic prominence. This sloping terrain likely (i.) induces large-scale diurnal warm anabatic and cool katabatic flows potentially affecting diurnal UHI dynamics in the PMA, especially in eastern suburbs at higher elevations (Gordon 1921; Brazel et al. 2005; Sun et al. 2009) and; (ii.) diminish the influence of possible smaller-scale thermally-driven UHI circulations as such flows are topographically constricted (Balling and Cerveny 1987; Fernando 2010).

In recent years, several studies have simulated near-surface UHI using physics-based numerical climate models over different spatial scales. Coupled mesoscale/regional climate models (e.g. the Pennsylvania State University/National Center for Atmospheric Research numerical model – MM5, or the Regional Atmospheric Modeling System – RAMS) initially investigated how surface LULC alterations affected near-surface summer air temperatures (Grossman-Clarke et al. 2005, 2008), or air temperatures over different seasons (Georgescu et al. 2008, 2009a, 2009b). Generally, higher nocturnal urban temperatures were simulated, although UHI intensities were generally underestimated with respect to observed data. A probable factor is that these mesoscale models are, to some degree, inaccurate in simulating both energetic and turbulent processes arising from micro- or local-scale complexities of the urban surface. With advances in computational and processing power, however, local-scale urban canopy models (UCM) that parameterize three-dimensional roof, wall and road surfaces can be readily coupled to mesoscale climate models (e.g. Masson 2000; Kusaka and Kimura 2004). In the PMA, Grossman-Clarke et al. (2010) applied the coupled WRF-Noah-UCM to investigate how LULC changes from 1973-2005 affected near-surface temperatures during selected extreme heat events, and subsequently found improved agreement between observed and modeled temperatures.

2.3.2: Biophysical consequences of UHI – approaches

After physical evidence confirmed a strong UHI effect within the PMA, a subsequent research theme focused on its biophysical impacts on urban residents. A major approach was to examine human discomfort and other impacts on flora and flora. In a study that included researchers from different scientific disciplines, Baker et al. (2002) linked increasing T_{min} UHI trends from 1948-2000 to detrimental impacts on human thermal comfort (e.g. increased cooling degree days and misery hours per day), flora (e.g. greater heat stress for plants) and fauna (e.g. reductions in both dairy milk production and arthropod development). The growing UHI also affected heat-related dispatch (HRD) call rates from residents. Analysis of 2001-2006 climate and HRD data taken from most of the PMA revealed that more calls occurred during times of elevated human comfort indices, especially during periods of higher nocturnal temperatures (Golden et al. 2008).

Another approach discussed UHI as a potential hazard to urban populations and investigates how physical data (e.g. elevated urban temperatures) relate to social data (e.g. socio-economic variations in urban population). A key question underpinning this research was whether this confluence resulted in disproportionate biophysical impacts such as health inequalities from heat exposure, which is potentially exacerbated by extreme summer temperatures in Phoenix. Several studies, which employed inter-disciplinary methods and researchers, examined intra-urban vulnerability to extreme heat (i.e. the relationship between a population's physical exposure to increasing temperatures with its adaptive capacity to this hazard) at local and regional spatial scales (Harlan et al. 2006; Ruddell et al. 2009; Chow et al. 2010). Generally, distributions of heat vulnerability varied spatially, with (i.) heat stress exposure being significantly and positively correlated with both larger population densities and heavily Hispanic populations, and negatively associated with access to open spaces, irrigated vegetation and median family income, and; (ii.) elderly, minority and low-income residents were more exposed to heat stress vs. younger, white Anglo, and more affluent counterparts.

Research of explicit UHI impacts on the demand and use of urban energy, transportation, and water in the PMA also exists. The increasing trend in UHI intensities and cooling degree days corresponded with greater commercial and residential air-conditioning demand, consequently increasing the total carbon emissions share from these sectors at greater rates relative to others from 1971-1998 (Golden 2004), as well as increasing mean annual homeowner costs from heating, ventilating and air-conditioning increased by 10% due to rising urban temperatures from 1949-2005 based on a DOE-2 model study (Golden et al. 2006). Othanicar et al. (2010) modeled UHI impacts on vehicular emissions in Phoenix, and found significant increases in evaporative hydrocarbon emissions over both summer and winter in 2004. Lastly, residential water use and demand have been shown to positively correlate to UHI intensity, especially for landscaping purposes (Balling and Gober 2007). For instance, a 0.6 °C (1 °F) increase in summer urban T_{min} was predicted to result in a 1098 liter (290 gallon) increase in residential lot water use per month within the City of Phoenix, via two empirical log-linear multiple regression models that have T_{min}, NDVI, and selected census tract housing and population characteristics as covariates (Guhathaurktha and Gober 2007).

2.3.3: Sustainable mitigation and adaptation to UHI - approaches

As the Phoenix UHI results in several mostly detrimental impacts with respect to urban sustainability[3], a recent major research theme was to consequently investigate applied techniques and methods in mitigating and/or adapting to warmer urban climates. One mitigation approach is the use of vegetated or "green" landscapes in suburban residential areas. Such landscapes are similar to the objectives of urban forestry initiatives implemented in other

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[3] A sustainable city can be defined as a settlement that is designed, built and managed in ways that, over time, are able to improve human health, quality of life and commerce without excessive consumption of natural resources (Martin 2008). This implies that municipal governments and residents attempt to prioritize environmental considerations equally with social and economic issues, and also aim for resource use efficiency towards societal benefit (Mills 2006).

North American cities (e.g. McPherson 2006), but use of non-native vegetation species for landscaping commonly occurs within suburban areas in the PMA, especially in older suburbs. Such “mesic” species require water-intensive irrigation in the PMA, especially during summer, but have significant observed (Brazel and Johnson 1980; Stabler et al. 2005; Martin 2008) and modeled (Gober et al. 2010; Chow et al. 2011) cooling influence on near-surface temperatures at micro- and local-scales. When compared to concrete and asphalt, mesic surfaces generally have greater evapotranspiration that increase latent heat fluxes, as well as increased soil moisture from permeable surfaces that reduce both thermal storage and long-wave outgoing radiation (e.g. Oke 1987). Landscapes that have trees with broad canopy cover can also reduce daytime temperatures through shading of incipient solar radiation (e.g. Akbari et al. 2001).

A major concern, however, is that mesic landscaping is relatively water-intensive compared to residential landscapes using either xerophytic or desert-adapted vegetation, and is a major contributor to high PMA per-capita residential water use that ranges from 856-1514 liters (226 to 400 gallons) per day, compared to the daily U.S. average of 379 liters (100 gallons) per capita (Yabiku et al. 2008). Further, residential water consumption is significantly correlated to meteorological conditions, with more water consumed outdoors under hot and dry conditions especially in predominantly mesic residential neighborhoods (Balling et al. 2008). Given its arid climate, current vulnerability to water scarcity and prolonged drought conditions (e.g. Morehouse et al. 2002), as well as future projections of a drier climate throughout the American Southwest (Wilbanks et al.

2007), wide-scale use of water to irrigate landscapes would substantially detract, rather than enhance, the PMA's sustainability.

Another UHI mitigation approach involves engineering thermophysical properties of construction materials (e.g. concrete and asphalt) to inhibit UHI development. These surface properties, such as albedo and emissivity, are modified with the aim of (i.) reducing absorption and storage of insolation and; (ii.) increasing thermal admittance and evapotranspiration (Golden 2004). This can be manifest through "white" roofs or pavements, or through use of large canopy structures that shade the surface. Unlike vegetated landscaping, these methods are not water-dependent and could potentially be readily applied at city-wide or regional scales. Several modeled simulations in the PMA revealed that increasing surface emissivity and albedo of typical urban construction materials resulted in largest magnitudes of nocturnal and daytime cooling respectively (Emmanuel and Fernando 2007; Gui et al. 2007; Silva et al. 2009). Another study examined the micro-scale cooling potential of vegetated surfaces and shade canopies covered with photovoltaic (PV) cells (Golden et al. 2007). While PV canopies provided a greater reduction of daytime temperatures vs. green surfaces, but there was little impact on nocturnal temperatures. Nonetheless, the PV cell canopies could contribute towards local sustainability by reducing energy consumption from non-renewable resources, as these can provide supplemental base load and peak power electricity for buildings, signage and municipal needs in the immediate area, depending on the system rating and available electricity generating potential hours.

2.4: Motivation for UHI research

We propose that the comprehensive scope of UHI research in the PMA reviewed hitherto resulted from several influences arising from either be extrinsic (i.e. motivation originating outside of the PMA) or intrinsic factors. A major extrinsic factor is that knowledge and theory from UHI – and general urban climatology studies – extracted from cities of similar (and dissimilar) climates undoubtedly contributed in formulating specific deductive research questions for Phoenix UHI research. Another factor would be that the rapid LULC change that occurred post-1945, combined with projected impacts of a warmer, drier American Southwest from global and regional climate change, are also relevant issues that focused attention on the potential UHI impacts. The prevalence of clear and calm synoptic weather conditions over the PMA throughout the year, and especially during summer, also favors the development of large UHI intensities. These factors, however, could also apply to other cities with similar circumstances. We thus note that there were three other specific and unique influences intrinsic to the PMA that were important in motivating UHI research.

First, there was a confluence of complementary interests between and within several local and national agencies keen on applied urban meteorological investigation within the PMA. These included departments or institutes that researched meteorology and climatology in Arizona’s major universities, the State Climate Office, the National Weather Service (NWS), the National Severe Storms Laboratory (NSSL), the Arizona Department of Environmental Quality (ADEQ), Salt River Project, a private-sector energy and water company (SRP), and municipal governments at city, county and state-level. The extent and duration of these partnerships appear to be unique to Phoenix, and were essential in expanding the scope of urban climate research within the PMA, especially in the demand and supply of urban climate data and information.

The first formal partnership was formed in 1977 between the NWS, the National Climatic Center and the Arizona Board of Regents to primarily supply and archive climate data from meteorological stations within the state, and to provide monthly climate summaries for users that continues to the present day. Another long-term partnership (between SRP, Arizona State University, and the State Climate Office) spurred and supported academic research into several aspects of urban climate, including UHI, urban air quality modeling, and solar energy potential in the PMA. A major objective of this research was the improvement of short-term weather forecasting models applied to urban areas. A partnership between the NSSL and the State Climate office also led to the formation of the Arizona Thunderstorm Chase (AZTC) project, a real-time storm monitoring program in the PMA that was run by university students and volunteers that gathered and transmitted thunderstorm data to NWS Phoenix (Cerveny et al. 1992). There was also strong demand for climate data – especially within urban areas – from city governments that required information for municipal policy issues such as air and water quality regulations, construction project designs, and energy and groundwater use within the PMA (Brazel 1999).

Partnerships within academic institutes, especially between science and social science disciplines, were also essential in driving recent UHI research.

These have been essential in guiding several recent research publications in the themes of UHI biophysical impacts, and its sustainable mitigation/adaptation. An important organization is the Central Arizona – Phoenix Long-term Ecological Research (CAP-LTER) project, a program of the National Science Foundation (NSF) that investigates the complexities of various human-ecological processes over different spatial and temporal scales within the PMA. It is also one of two LTER sites that are based in urban areas (Brazel and Heisler 2009). CAP-LTER has fostered an academic environment that aided communication and intellectual cross-pollination of ideas and methods between urban climatologists with other scientists and social scientists involved in UHI-related research. This was stressed by Mills (2006) and Oke (2006b) as critical for the progression of the study of urban meteorology and climatology.

Second, this convergence of interest for urban climate data also precipitated in the development of an extensive meteorological station network scattered throughout the PMA over a variety of LULC types (Figure 4). A major reason for this were requests for urban climate data originating from the private sector in the early 1990's, as SRP was interested in examining intra-urban variations of insolation and temperature data for potential solar energy applications. Other agencies were also interested in real-time, hourly climate data for agricultural or horticultural purposes in cities within the state (e.g. the University of Arizona), or for air pollution and flood hazard warnings in the PMA (e.g. Maricopa County government). Demand for these high-resolution data could not be easily provided by the NWS, as most co-operative weather stations primarily recorded only basic temperature and precipitation data.

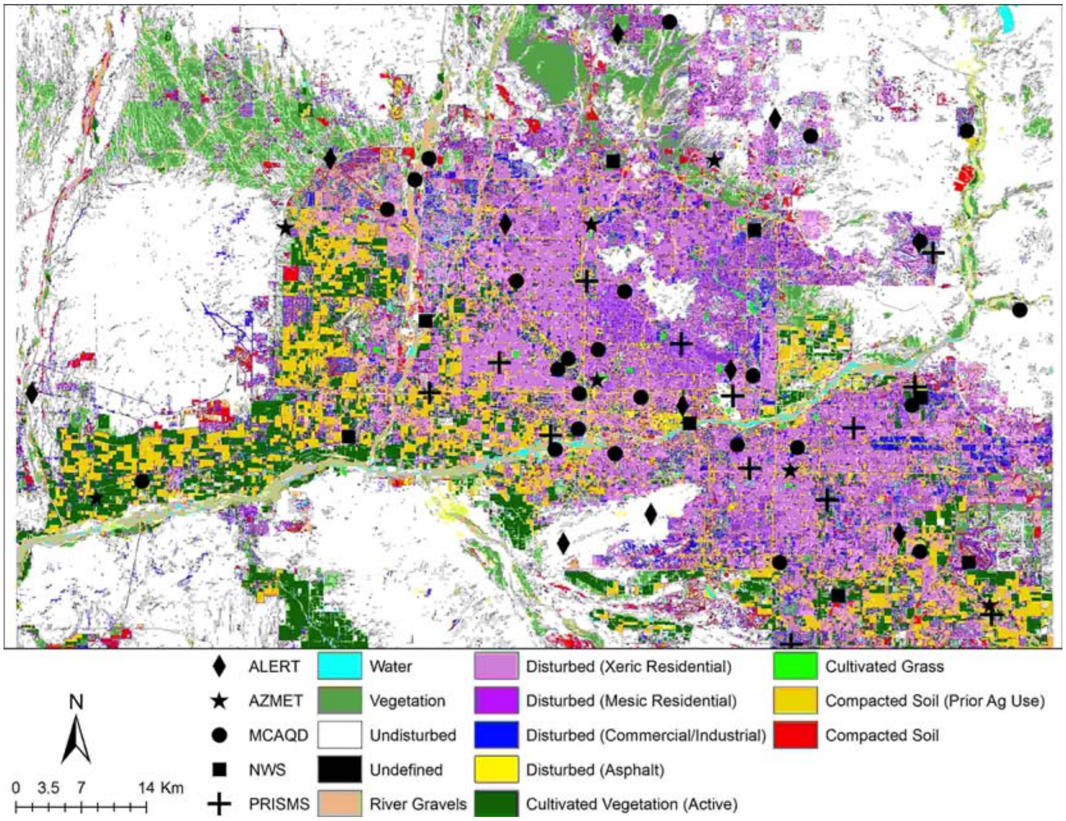

Figure 4: 2005 LULC classification of the Phoenix Metropolitan Area (Buyantuyev 2005) with locations of operational urban meteorological stations. ALERT = Automated Local Evaluation in Real-Time; AZMET = Arizona Meteorological Network; MCAQD = Maricopa County Air Quality Department; NWS = National Weather Service Automated Surface Observing Systems; PRISMS = Phoenix Real-time Instrumentation for Surface Meteorological Studies

Subsequently, these stakeholders developed networks of real-time automated weather stations sited within the boundaries of the PMA that provide quality-controlled climate data that are available for public users. As of end 2010, there are 70 stations in operation that have data available for interested researchers either online or through contact with the relevant agency (Table 2). Several of these networks have been in operation since 1990, and the duration of available high-quality near-surface climate data facilitates research into spatial and temporal aspects of UHI (e.g. Brazel et al. 2007), that would be problematic in other cities lacking such a dense network.

Table 2: Listing of urban meteorological station networks based within the PMA that were operational in 2010.

Station network name	Operated by	Original network objective	Number of PMA stations in 2010
PRISMS (Phoenix Real-time Instrumentation for Surface Meteorological Studies)	Salt River Project (SRP)	Energy demand and solar research	16
AZMET (Arizona Meteorological Network)	University of Arizona	Agricultural and horticultural data	8
AQD (Air Quality Department)	Maricopa County	Urban air pollution	22
FCD (Flood Control District) ALERT (Automated Local Evaluation in Real-Time)		Urban flood hazard control	16
ASOS (Automated Surface Observing Systems)	National Weather Service (NWS)	Surface weather observation	8
TOTAL			70

Third, there is relatively strong media interest on UHI issues in Phoenix, possibly as a consequence of its hot arid climate and also from concerns over future climate change impacts in the region. This is manifest in the broad extent of journalistic coverage of UHI in both established print and broadcast media that appears to be uncommon in other cities. An archival search of the largest newspaper in the state (*The Arizona Republic*) shows that 187 articles related to "urban heat island" were published from January 1999 to September 2010. These included short, factual reports of UHI impacts ("2010 Phoenix summer one of hottest ever due to overnight lows", September 6 2010), longer editorial columns ("Let's cool it! We got ourselves onto this heat island, we can get ourselves off it", September 14 2003), guest opinion columns from academic researchers ("Urban heat island affects Phoenix all year-round", September 22 2007), and in-depth coverage of UHI research ("Cities are key culprits in weather shifts", January 11 2009). Television meteorologists from several PMA television network channels have also regularly highlighted the impacts of UHI, both in on-air broadcasts (e.g. KSAZ-TV (2010) "Heat Island Effect is Warming the Valley") and by having basic, informative UHI-related content online that is regularly updated e.g. KNXV-TV (2010).

2.5: Policy applications

The application of municipal policies based on UHI research is important with respect to reducing urban vulnerability and improving its sustainability. These policies can also be relevant in responding to negative global climate change impacts. For instance, alterations to regional weather and climate from cities have been viewed as an analog for global climate change impacts (Changnon 1992), especially as increased urban metabolism (e.g. emissions from urban transportation) and drivers of LULC change (e.g. residential construction at urban suburbs) are potential sources of greenhouse gases. The notable corollary is that cities can also generate solutions via reduction or effective management of urban resources that reduces greenhouse gas emissions (Mills 2007). Thus, documenting the effectiveness of sustainable UHI mitigation/adaptation policies in Phoenix can be a useful resource for other rapidly developing cities with significant UHI.

Within the PMA, several municipal governments have actively applied UHI research findings onto urban planning and policy to improve urban sustainability via (i.) reducing UHI intensities, energy consumption and near-surface air pollution, and (ii.) increasing thermal comfort at street levels. This could be attained via design plans for future urban growth and development that propose appropriate building forms, street design, urban forestry, shade structures, and development standards. Two examples from the City of Phoenix illustrate how prior UHI research largely done by Arizona State University scientists contributed to policies aimed towards improving urban sustainability.

First, the 2008 Downtown Phoenix Urban Form Project was a collaborative process that explicitly discussed thermal benefits arising from optimal building forms and massing standards, reflective paving and street materials, as well as supplementary shading structures at street level. Ultimately, the project proposed future urban zoning policies and codes aimed at reducing heat discomfort within the city core (City of Phoenix 2008). Second, in 2010, the Tree and Shade Task Force developed a plan (SHADE Phoenix) that provided a roadmap towards an average of 25% shade canopy coverage for the entire city by

2030. They recommended the use of urban forestry techniques and physical shade structures that would mitigate the UHI (City of Phoenix 2010). Both these recommendations that promoted a sustainable urban climate were adopted by the City council within the same year of publication.

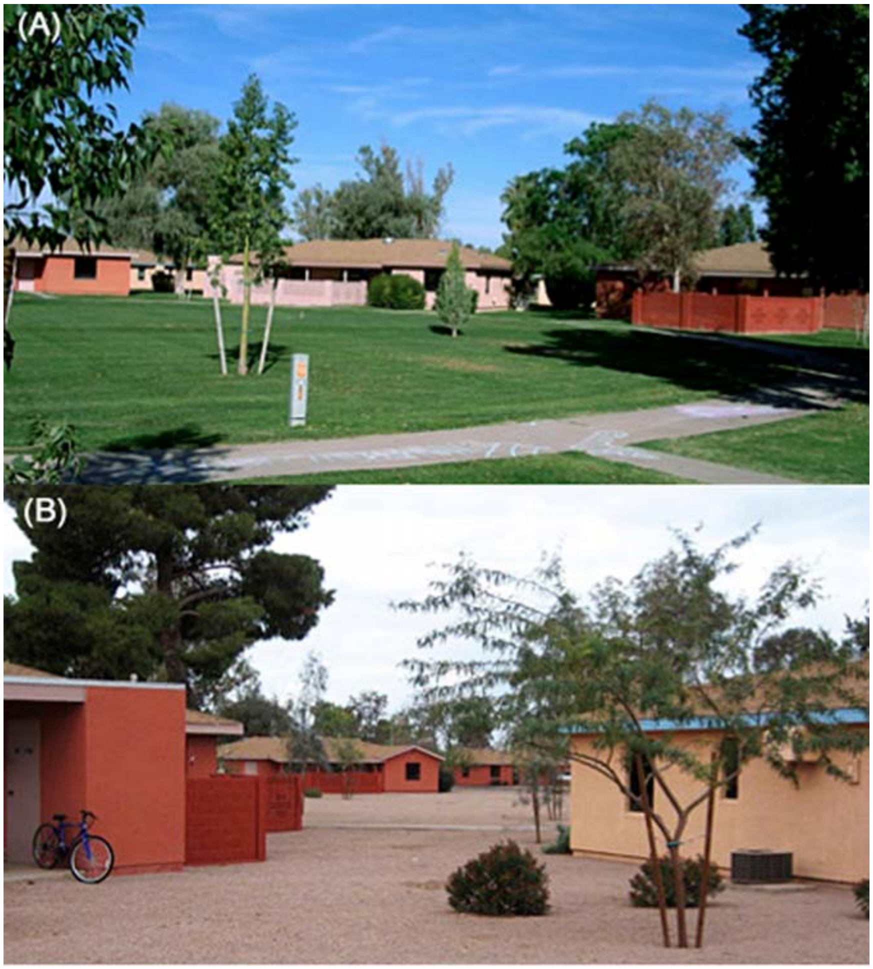

Figure 5: Typical mesic (A) and xeric (B) residential landscaping in the PMA. The "xeriscaping" policy promoted by several PMA cities involves conversion of water-intensive plants to desert-adapted, low-water vegetation (Source: CAP-LTER).

Apart from future development plans, other initiatives and policies explicitly aimed at mitigating UHI also exist in extensively developed residential suburbs that comprise the majority of PMA land-use. Several municipal governments (e.g. the cities of Chandler, Glendale, Peoria, Scottsdale, and Tempe) have actively promoted urban sustainability by encouraging homeowners with extensive mesic landscaping to convert to low-water demand desert-adapted vegetation ("xeriscaping") (Figure 5). For instance, as part of a larger sustainability initiative, the City of Mesa implemented a popular rebate policy in 2007 that offered $500 for homeowners to convert at least 46.5 m^2 (500 square feet) of mesic-grass to xeric landscaped yards (City of Mesa 2010). These cities work in conjunction with the Arizona Department of Water Resources, which provide a database of low-water use plants for residential homeowners in the PMA. A common aim among these municipal programs is to reducing residential water consumption while maintaining a comfortable micro-scale thermal environment for homeowners.

2.6: Concluding summary

Since the first published study by Gordon (1921) that mapped near-surface temperature fields in Phoenix, UHI research in the PMA has progressed in scope and content. Investigation of its physical characteristics through observational and modeling methods has yielded several theoretical insights of the form and dynamics of UHI with respect to rapid LULC change and the influence of topoclimates. These scientific investigations also subsequently influenced research into its biophysical impacts, as well as on effective sustainable UHI mitigation methods. The results, as well as methodologies from these applied and inter-disciplinary studies, are potentially transferable to cities in arid and other climates. We suggest that the large body of work (~55 published peer-reviewed studies) resulted from several extrinsic and intrinsic factors; the latter are influences specific to Phoenix that includes partnerships between agencies with a common interest in understanding and applying urban climate research, an extensive urban meteorological network that yielded high-quality data, and strong local public interest in UHI. The cumulative knowledge attained from these research themes have successfully translated, and applied, into recent municipal policy that relates to broader sustainable initiatives.

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CHAPTER 3: OBSERVING AND MODELING THE NOCTURNAL PARK COOL ISLAND OF AN ARID CITY: HORIZONTAL AND VERTICAL IMPACTS[4]

3.1: Abstract

We examined the horizontal and vertical nocturnal cooling influence of a small park with irrigated lawn and xeric surfaces (~3 ha) within a university campus of a hot arid city. Temperature data from 0.01-3 m heights observed during a bicycle traverse of the campus were combined with modeled spatial temperature data simulated from a 3-dimensional microclimate model (ENVI-Met 3.1). A distinct park cool island, with mean observed magnitudes of 0.7-3.6 °C, was documented for both traverse and model data with larger cooling intensities measured closer to surface level. Modeled results possessed varying but generally reasonable accuracy in simulating both spatial and temporal temperature data, although some systematic errors exist. A combination of several factors, such as variations in surface thermal properties, urban geometry, building orientation, and soil moisture were likely responsible for influencing differential urban and non-urban near-surface temperatures. A strong inversion layer up to 1 m over non-urban surfaces was detected, contrasting with near-neutral lapse rates over urban surfaces. A key factor in spatial expansion of the park cool island was the advection of cooler park air to adjacent urban surfaces, although this effect was

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[4] Co-authors of this manuscript were Ronald L. Pope, Chris A. Martin, and Anthony J. Brazel; this paper was submitted to *Theoretical and Applied Climatology* in July 2009 and published in January 2011.

mostly concentrated from 0-1 m heights over urban surfaces that were more exposed to the atmosphere.

3.2: Introduction

Parks and other green-spaces located within cities generally have lower surface and ambient air temperatures compared to typical urban surfaces such as concrete, tarmac and asphalt (e.g. Jauregui 1990/1991; Saito et al. 1990/1991). This is primarily due to alterations to the surface energy balance, with relatively more radiant energy partitioned into the latent heat and/or heat storage terms as opposed to sensible heat (Oke 1987). Other reasons why parks/green-spaces might be cooler than the surrounding structures include greater direct shading from vegetation with large canopies that reduces surface temperatures, a higher sky view factor relative to urban surfaces allowing for unimpeded radiative cooling to the sky, and a lack of heat from combustion sources (Spronken-Smith and Oke 1999; Shashua-Bar et al. 2009).

This phenomenon of patchy, cooler areas within the urban mosaic is often termed the park cool island (PCI). Increasingly, urban planners are aware that managed PCIs through the use of urban green-spaces could be a useful applied tool towards mitigating detrimental impacts stemming from the urban heat island (UHI), especially within tropical and sub-tropical cities of large spatial extent (e.g. Emmanuel 2005). Past research of PCI effects mostly relied on observational studies focusing on the spatial distribution of temperatures with respect to adjacent urban surroundings, with much fewer studies either examining the vertical form of PCI, or modeling the impacts of green spaces on the urban environment.

In this study, we examined both horizontal and vertical nocturnal temperature differences at different heights between a non-urban, largely vegetated surface and its urban surroundings. We analyzed horizontal micro-scale temperature fields and vertical (i.e. lapse rate) profiles within a study area located in an arid desert climate. We obtained PCI intensities through two methods: (i.) direct, relatively high frequency (1 s) temperature measurements obtained from a bicycle traverse over different land-use types, and (ii.) modeling study area temperatures through a three-dimensional numerical micro-meteorological model (ENVI-Met 3.1) with inputs adapted to local soils and vegetation. A secondary objective was to evaluate the accuracy of modeled vs. observed temperatures from the traverse and a nearby meteorological station. This study aims to improve the understanding of PCI effects for a desert city, of which research is relatively deficient, compared to other urban climates.

3.3: Literature review

PCI can be measured either through surface or air temperature differences between urban surroundings with the park or green-space ($\Delta T_{u\text{-}p}$). Distinct differences of surface temperatures between parks and adjacent urban areas often result in dynamic variations of $\Delta T_{u\text{-}p(surface)}$ (Roth et al. 1989). Variations of $\Delta T_{u\text{-}p(air)}$ are strongly coupled with underlying surface types at micro-scales, although greater turbulence and advection reduces magnitudes of surface-air thermal coupling, especially at distinct borders between surface types at micro-scale levels (Jansson et al. 2007). Higher wind-speeds and the resulting local-scale turbulent mixing also dilutes the maximum magnitude of $\Delta T_{u\text{-}p(air)}$ relative to $\Delta T_{u\text{-}p(surface)}$, but may also expand the influence of the PCI beyond the physical boundaries of the park (Oke 1989; Eliasson and Upmanis 2000). Magnitudes of mean $\Delta T_{u\text{-}p(air)}$ range from 1.5-4 °C (Sham 1987; Upmanis et al. 1998; Jonsson 2004), but maximum intensities can be as large as ~7 °C during summer nocturnal periods in Sacramento, California (Spronken-Smith and Oke 1998).

The size of the park or green-space, topography, wind-speeds and vegetation types are factors influencing PCI magnitudes and development. Larger parks are generally associated with greater PCI intensities (Barradas 1991; Jauregui 1990/1991), and magnitudes of $\Delta T_{u\text{-}p(air)}$ inversely correlate to wind-speeds (Spronken-Smith 1994). Topographic variations potentially affect regional airflow into parks at different spatial scales, such as by large-scale nocturnal katabatic drainage from mountains to a valley city that reduces urban air temperatures adjacent to parks (Kirby and Sellers 1987). Vegetation types in parks also affect the timing of maximum PCI (Spronken-Smith and Oke 1998), with (i.) parks with substantial tree canopies having greatest cooling impacts during the afternoon, (ii.) mixed-use, garden or savannah parks having PCI maxima around sunset, and (iii.) open grass parks having observed PCI maximums around sunrise.

Of particular interest are geographical differences in $\Delta T_{u\text{-}p}$ within cities located in hot arid vs. other climates. The scarcity of surface and atmospheric moisture, combined with intense diurnal surface radiative exchanges, are significant qualitative differences affecting PCI development in desert cities (Pearlmutter et al. 2007). Latent heat fluxes from surface evapotranspiration in desert cities are much lower relative to urban areas in other climates, but this strongly depends on irrigation availability for parks in these cities. For instance, daytime summer latent heat fluxes in Tucson, Arizona, where landscape irrigation of suburban residential green-spaces is prevalent, accounted for 25-35% of the daytime surface energy balance (Grimmond and Oke 1995). In contrast, a similar contribution to the surface energy balance of Mexicali, Mexico, which lacked water availability for irrigation, was only ~10% (Garcia-Cueto et al. 2003). Irrigation of green spaces is therefore important for daytime cooling through evapotranspiration within desert cities (e.g. Pearlmutter et al. 2009), especially combined with windy conditions that expands the "oasis effect" of PCI (Spronken-Smith et al. 2000). Increases in surface and soil moisture from irrigation also alter the surface thermal admittance of parks (μ), an important property measuring the ability of a surface to accept or release heat (Oke 1987). Higher (lower) soil moisture content results in higher (lower) μ, resulting in reduced (increased) urban vs. green-space near-surface temperature differences (Chow and Roth 2006). As nocturnal park cooling appears to be more dependent on surface conduction and radiation processes as opposed to evapotranspiration (Oke et al. 1991; Spronken-Smith and Oke 1999), the timing of irrigation of parks post-sunset potentially affects diurnal PCI development and nocturnal PCI intensities in arid cities.

The study of PCI impacts within arid urban areas is important, given the increasing population and urban development seen in several Middle-Eastern and North American desert cities in recent years, including Phoenix, Arizona (Gober 2006). It is also essential to examine methods and techniques of cooling urban landscapes (e.g. Shashua-Bar et al. 2009), which include increasing and maintaining urban green-spaces. It is thus unsurprising that urban parks have great potential in mitigating detrimental nocturnal UHI impacts in desert cities, as well as reducing overall urban energy consumption (Kurn et al. 1994), especially if urban vegetation are well-maintained (Muellar and Day 2004). In Phoenix, the placement, design and upkeep of urban green-spaces are important in reducing UHI intensities, and in potentially improving human health and quality of life without excessively consuming natural resources. Thus, they are a key component in developing sustainable urban landscapes for this large metropolitan area (Stabler et al. 2005; Martin 2008).

Previous study methodologies investigating thermal impacts of urban parks generally used data obtained from station temperatures and/or vehicular traverses (e.g. Sham 1987; Upmanis et al. 1998; Jonsson 2004), or through hardware scale modeling (Spronken-Smith and Oke 1999; Pearlmutter et al. 2009). These methods usually focus on examining both spatial form and intensities of ΔT_{u-p} across different urban land-use types. Much fewer studies (e.g. Jansson et al. 2007), however, examine the vertical impacts of PCI, i.e. analyze temperature profiles or lapse rates over different surface types within the urban canopy layer (i.e. from surface to mean roof height). Compared to these research methods, there has also been hitherto less work into modeling ΔT_{u-p}, especially at micro-spatial scales (i.e. linear and areal extents ranging from approximate 1 to 10^2 m or m^2) (Oke 2006a). Some research of micro-scale numerical modeling of urban vegetation impacts exist, although these are limited to simulations adding individual street trees in Colombo, Sri Lanka, and in downtown Phoenix (Emmanuel and Fernando 2007) or via increasing rooftop or vertical vegetation density in Singapore (Wong and Jusof 2008).

3.4: Materials and methods

3.4.1: Study area

The study was conducted in the Tempe campus of Arizona State University, located within the Phoenix metropolitan area (33.416 °N, 111.931 °W, 355.4 m above sea level). A 23 ha section of the campus centered on the Student Recreation Complex (SRC) field was selected as our study area (Figure 6). The ~3 ha-sized field is a level urban green-space mostly covered by lawn grass (0.05-0.1 m heights) of either Bermuda (summer) or Rye (winter) species, which are similar to grasses used for residential landscaping throughout suburban Phoenix. Parts of the field were exposed bare sandy-loam soil, especially in the center and along three of its four corners. The field was bounded by a wide variety of medium height trees (5-10 m) (e.g. Seville sour orange, *citrus aurantium,* and Chinese pistache, *pistacia chinensis*) with a wide canopy and dense foliage along the north, south and east field perimeters, and by taller trees (20-25 m) (e.g. Coolibah (*eucalyptus microtheca*) and Mexican fan palm, *washingtonia robusta*)

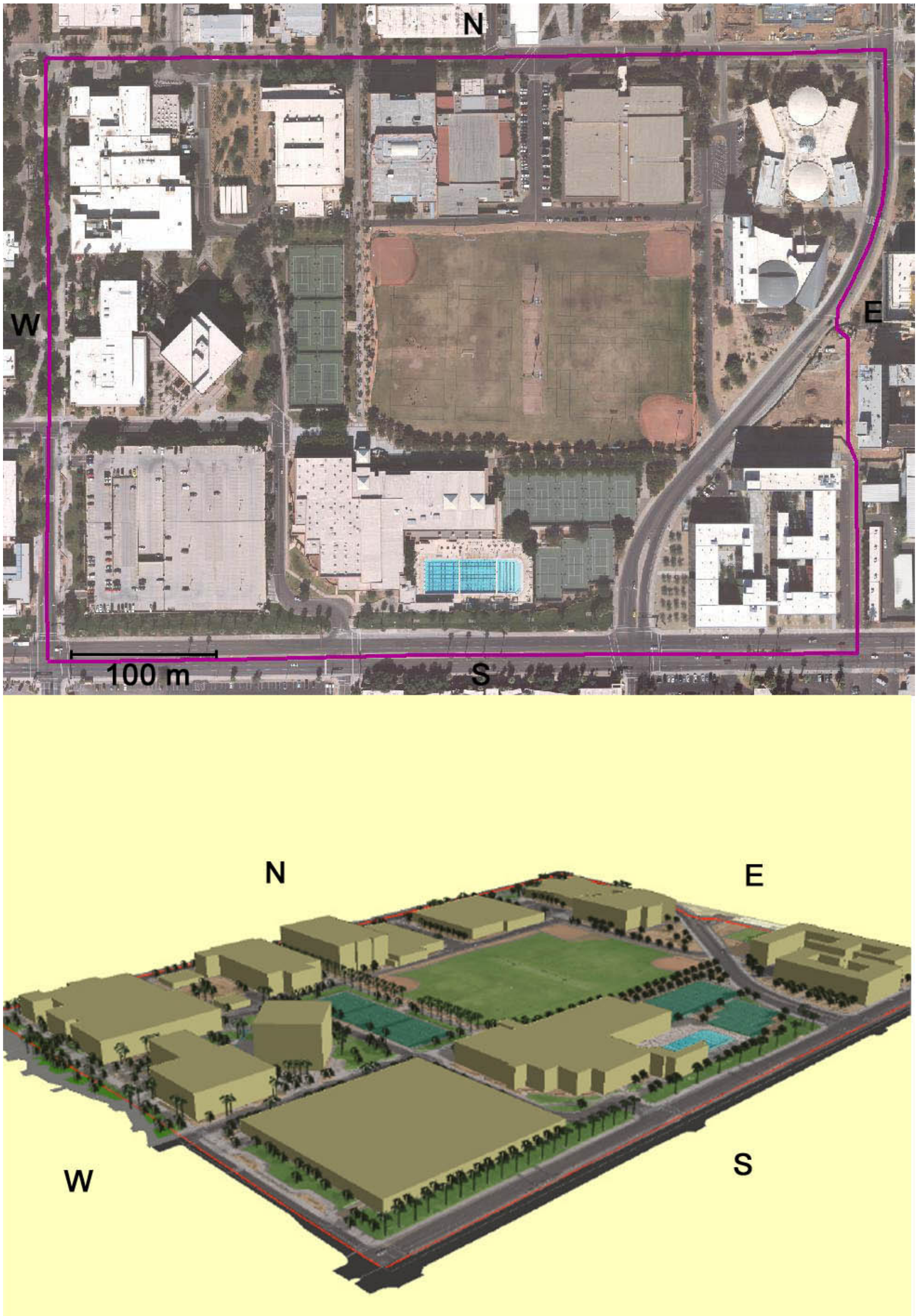

Figure 6: March 2007 aerial photograph of the 23 ha study area (demarcated by bold line) within the Arizona State University - Tempe campus (top), and 3-d model of study area generated by ArcView 9.3 (bottom).

along the west field perimeter. Other smaller lawn grass plots with medium-height trees of similar height e.g. blue Palo Verde (*parkinsonia florida*), southern live oak (*quercus virginiana*), and desert fan palm (*washingtonina filifera*) lined several roads and boulevards, especially on the northern and southern boundary areas. These vegetation species are also commonly found in residential areas for landscaping. Buildings in the study area varied between 5-30 m above surface level (a.s.l.), with a mean height of ~10 m. A section of several hard-court tennis courts and an Olympic-sized swimming pool were located to the west and south of the field.

Using ArcView 9.3 GIS, we created a 3-dimensional (3-d) model by digitizing an aerial photograph of the study area as well as from fieldwork reconnaissance (Figure 6). This model was subsequently used in traverse route design (Figure 7), with the objectives of extensive temperature sampling coverage over different surface types, such as urban (e.g. asphalt, concrete and tennis court) and non-urban (e.g. xeric and lawn grass) surfaces categorized within the study area. In addition, temperatures on surfaces confined within a street or pavement canyon between buildings (i.e. urban canyons) were classed in a separate category. To quantify the aspect ratio of building height vs. spacing in these urban canyons, sky-view factors were estimated using 3DSkyView, an ArcView 3.2 GIS program extension written by Souza et al. (2003). This program has been shown to produce more accurate results than other geometric estimation techniques, with similar, if slightly elevated, results when compared with actual field data. Minimum (mean) sky-view factors in these canyons were 0.5 (0.7), indicating low to medium density urban development in the study area.

Figure 7: Map of traverse route and classification of different surface types within study area.

3.4.2: Observed temperature data

An instrument setup similar to Sun et al. (2009) was utilized to obtain and geo-code spatial temperature data. We used the TR-72U temperature/relative humidity sensor-datalogger (T&D Corporation), which had a specified resolution (accuracy) of 0.1 °C (± 0.3 °C), and the BT-Q1000 GPS travel recorder (Qstarz) which noted geographical coordinates of latitude, longitude and altitude with a reacquisition rate of ~1 s. Four TR-72U sensors were attached to a metal pole before being vertically mounted to a bicycle at 0.01, 1, 2, and 3 m heights a.s.l..

As these sensors were not aspirated, it was also important that measurements occurred when air was not completely stagnant during the study to minimize lags in sensor response. The GPS system was also attached to the pole to record geographical coordinates of every temperature sampling point. Each TR-72U sensor and the Q1000 recorder was synchronized and programmed to sample temperatures and geographical coordinates at 1 s intervals. The TR-72U sensors were subject to pre- and post-fieldwork calibration to ensure that measurements were within manufacturer specifications.

The traverse occurred during the early morning (0530-0630 h) on October 28, 2007, as large magnitudes of ΔT_{u-p} are expected *a priori* during minimum temperature conditions given the open grass park that constitutes most of the SRC field. Cloud-free skies and generally low E winds of 0.4-0.8 m s^{-1} at 10 m above surface level were recorded during the traverse, which minimized meteorological impacts on both the PCI and UHI (Spronken-Smith and Oke 1998). These ambient weather conditions near the study area were recorded at the Tempe meteorological station of the Maricopa County Air Quality Department (MCAQD). The station was directly adjacent to an ~8 ha park mostly consisting of irrigated lawn grass, and was located within a low-density suburban residential neighborhood with predominant mesic landscaping ~670 m SSW of the SRC field. We therefore assumed station data to be representative of general near-surface meteorological conditions of our study area. Hourly temperatures from the MCAQD Tempe station were used to obtain time-series data for the study area. The study took place during a night when the SRC field was not irrigated, although we could not ascertain if other smaller green-spaces within the study area were watered.

We recorded ~3100 temperature datum points per sensor during the traverse, resulting in a total of ~12400 points for all four sensors. These data were consequently geo-referenced into the previously created GIS model for data analysis. Each datum point could therefore be categorized with its respective surface classification (Table 3). Mean temperatures for each sampling point were derived, together with mean vertical lapse rates for each urban and non-urban surface type.

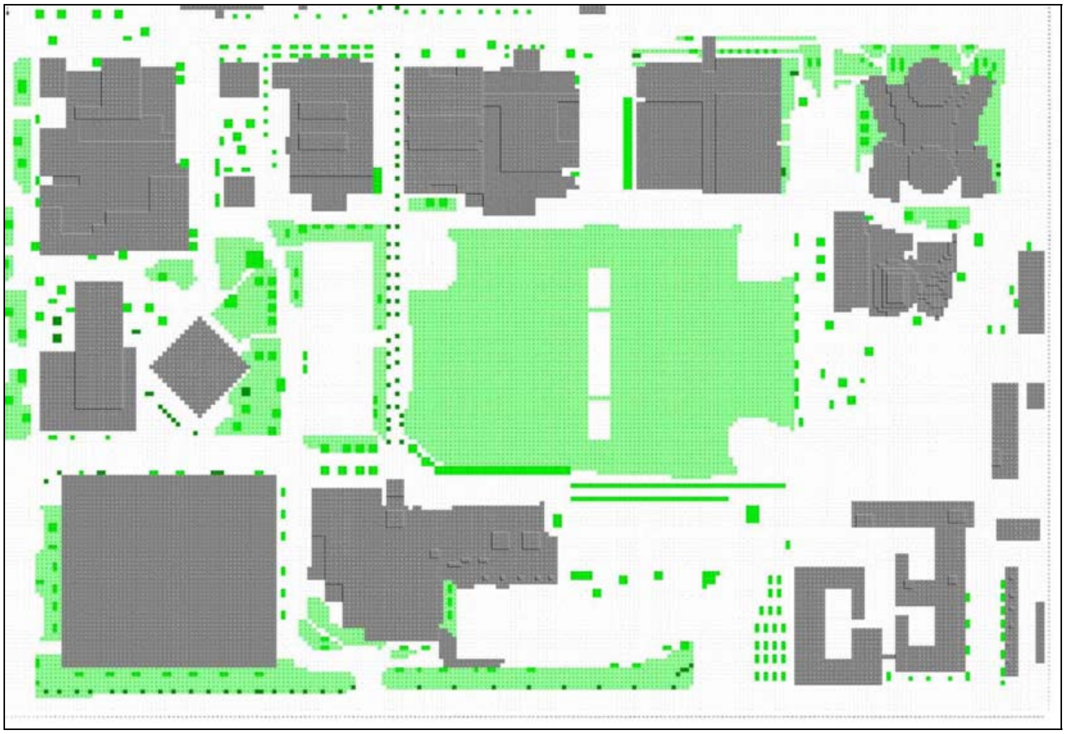

Figure 8: Part of the area input file for ENVI-Met simulations which was based on Figures 6 and 7. Individual grid cells sizes were 2.5 x 2.5 x 5 m.

3.4.3: Microclimate model simulation

We selected the ENVI-Met urban microclimate model (version 3.1, Bruse 2010) to simulate soil, surface and vegetation interactions within the urban canopy layer (i.e. below mean roof height). It is a 3-dimensional, non-hydrostatic, prognostic numerical model based on fundamental fluid-dynamic and thermodynamic laws (Bruse and Fleer 1998). Typical horizontal resolutions are 0.5-10 m, and simulations are normally run for 24-48 h, with a maximum time step of 10 s (Bruse 2009). Analysis of small-scale physical interactions between individual buildings, surfaces, soils and vegetation is thus possible at these modeled spatial and temporal resolutions.

Table 3: Surface characteristics for classification of traverse data.

Land-use type	Description of surface over which sampling occurred	No. of traverse sampling points
Urban surfaces		
Asphalt	Dark-colored road surfaces, mainly used by vehicular traffic	1110
Concrete	Lighter-colored pavement used by pedestrians	1021
Tennis courts	Hard-court green colored surface composed of asphalt with rubber compound for cushioning	243
Urban Canyons	Urban surface confined within buildings with restricted exposure to sky; minimum (mean) sky-view factor is 0.5 (0.7)	281
Rural surfaces		
Xeric	Surface with exposed sandy-loam soil without lawn cover	74
Lawn	Surface planted with lawn grass (Bermuda or Ryegrass species)	612

The model requires a user-specified area input file that defines the 3-d geometry of the model environment such as individual buildings and building heights, vegetation, soil and surface types etc. (Figure 8), which were derived from Figures 6 and 7. Although simulated concrete and asphalt surfaces in Figure 7 could be input into the model, a modeled surface type similar to the tennis court surface could not be found; instead, grid cells with this surface were classed as concrete surfaces. We also selected a relatively high resolution for individual grid cells (2.5 x 2.5 x 5 m) to complement the observed temperature data resolution. The area input file was nested within four nesting grids (with the predominant soil type) for numerical stability during model runs. We initially used the vegetation database included in the model defaults when configuring the area input file; however, these database characteristics, such as for normalized vegetation leaf area density data, were based on temperate forest and crop stands (M. Bruse, pers. comm.), which have little relevance to vegetation types found within an arid city. We therefore surveyed vegetation within the study area to empirically estimate leaf area density based on field observations with a Li-Cor LAI-2000 plant canopy analyzer, and derived vertical LAD distributions for each vegetation species based on the method proposed by Lalic and Mihailovic (2004) (Table 4). These database alterations subsequently allowed for input of local vegetation into ENVI-Met.

Apart from these vegetation data, the model also required local soil, meteorological and building input parameters (Table 5) for model initialization. Temperature and relative humidity (RH) at 2 m a.s.l., 10 m a.s.l. wind speed and direction data from the MCAQD Tempe station were used as initial model inputs, together with soil temperature and soil RH data from the Mesa station of the

Arizona Meteorological network (AZMET 2010). This station was ~6.5 km away from the SRC field and assumed to have similar soil profiles to the study area (i.e. sandy-loam soils). Specific humidity at 2500 m a.s.l. was estimated via data from the NCEP/NCAR reanalysis project at the NOAA/ESRL Physical Sciences Division (NOAA 2010). Lastly, building interior temperatures, mean heat transmission (i.e. thermal conductivity divided by mean wall or roof width), and roof/wall albedo values were estimated from existing table-base data (e.g. Oke 1987), and from field reconnaissance observations.

Table 4: Observed leaf area density (LAD) data for selected trees within study area.

Common name	Species	LAD_{max} (*Standard Error*) (m^2 m^{-3})	LAD_{max} height (m)	Mean tree height (m)
Bottle tree	*Brachychiton populneus*	3.23 (*0.12*)	2.25	7.75
Seville sour orange	*Citrus aurantium*	4.83 (*0.18*)	0.5	5
Coolibah	*Eucalyptus microtheca*	2.59 (*0.13*)	2.75	8.75
Shamel ash	*Fraxinus uhdei*	2.46 (*0.35*)	3	12
White mulberry	*Morus alba*	3.77 (*0.14*)	2.75	9
Thornless mesquite	*Prosopis hybrid*	2.92 (*0.11*)	2.5	9
Blue Palo verde	*Parkinsonia florida*	1.85 (*0.13*)	2	7.5
Southern live oak	*Quercus virginiana*	3.02 (*0.09*)	3	9.25
African sumac	*Rhus lancea*	4.39 (*0.24*)	2.25	8.25
European olive	*Olea europaea*	3.39 (*0.14*)	2.25	8.25
Chinese pistache	*Pistacia chinensis*	2.79 (*0.11*)	1.75	4.5
Aleppo pine	*Pinus halepensis*	2.68 (*0.18*)	2	4.75
Chinese elm	*Ulmus parvifolia*	1.68 (*0.12*)	2.75	8.5

Table 5: Selected input parameters for ENVI-Met simulations.

Category	User input during simulations
Meteorological inputs	
Wind speed and direction 10m above ground	0.8 m s^{-1}/85°
Approximate roughness length of study area	0.5 m
Specific humidity at 2500 m a.s.l.	2.75 g kg^{-1}
Relative humidity at 2 m a.s.l.	20%
Initial atmospheric temperature	290.3 K
Soil inputs	
Initial soil temperature at upper layer (0-20 cm)	293 K
Initial soil temperature at middle layer (20-50 cm)	294 K
Initial soil temperature at lower layer (below 50 cm)	295 K
Relative humidity upper layer	25%
Relative humidity middle layer	30%
Relative humidity lower layer	35%
Building inputs	
Building interior temperature	303 K
Mean heat transmission[1] of walls	1.7 $Wm^{-2} K^{-1}$
Mean heat transmission of roofs	6.0 $Wm^{-2} K^{-1}$
Mean wall albedo	0.3
Mean roof albedo	0.4

[1]: Estimated thermal conductivity of building material (W m^{-1} K^{-1}) divided by mean wall thickness (m)

We ran a model simulation for 24 h starting from sunrise (0600-0600 h; Oct 27-28, 2007) with updated surface data every 60 s. We subsequently analyzed model output at 0530 h, coinciding with the start of the bicycle traverse. Modeled potential temperatures at 0 m (surface), 1, 2 and 3 m were extracted as geo-referenced (X-Y co-ordinate reference) text-based .dat files using the accompanying LEONARDO program (V. 3.75 Beta) in the ENVI-Met software package, and were converted to absolute temperatures using Poisson's equation. Using the ASCII to raster tool in ArcView 9.3 GIS software, these files were converted and entered as raster files with 2.5 m x-y grid cells. The raster files were geo-referenced with the other map layers; warm features of the model output, i.e. buildings, were prominent in the raster and created excellent spatial references. This geo-referencing had an average root mean square error (*RMSE*) of 1.45 m; this error was both unavoidable and systematic, and is the result of 2.5 m gridded layers being geo-referenced to a discrete continuous map surface. Following geo-referencing, the raster grid was converted to a polygon feature class so that it could be spatially joined with the observed sample point layer. In this manner each of the ~3100 datum points at the 0.01, 1, 2 and 3 m elevations could be directly compared with corresponding ENVI-Met model output.

3.5: Results

3.5.1 PCI effect – observations and modeling

Both data from the bicycle traverse and from the ENVI-Met simulations illustrated a distinct PCI that developed over the SRC field. Observed temperatures from 0.01 and 2 m heights showed the SRC field and the adjacent west tennis court having cooler temperatures compared to the surrounding buildings, pavements and urban canyons (Figure 9). Temperatures at 2 m heights were also generally warmer when compared to the surface, especially over the lawn and xeric surfaces. The approximate maximum difference in temperature at 0.01 m (2 m) between the SRC field and its urban surroundings was ~5.8 °C (3.1

Figure 9: Temperatures observed from traverse for 0.01 (top) and 2 m heights (bottom) from 0530-0630 h.

°C), although there were relatively large variations in temperature over the urban surfaces adjacent to the field. We observed notable temperature differences within the field, with a cooler "core" in its center compared to its warmer perimeter adjacent to concrete or asphalt surfaces. Slightly cooler urban temperatures were observed W of the field and tennis courts, possibly indicating the effect of advection from easterly wind-flow, with urban canyon temperatures in the western section of the study generally being ~1 °C cooler compared to the eastern section.

Simulated temperatures from ENVI-Met also showed a PCI, albeit with lower approximate maxima of 3.6 °C and 2.9 °C at surface and 2 m heights respectively. Cooler temperatures were observed over the field and tennis courts, and a similar shift of cold air from advection from E-W was present (Figure 10). Temperatures at the surface were generally cooler than at 2 m heights, with lower temperatures at the center of the SRC lawn field as compared to its xeric surfaces. Colder temperatures were present along the eastern part of the study area, in contrast to observed temperature data, but this was most likely a consequence of the model's nesting grids of sandy-loam soils along its boundaries coupled with the constant E wind flow during the simulation period. Pockets of warmer air were observed within urban canyons in the western part of the study area, especially within N-S orientated canyons, which possibly resulted as a lee effect from buildings acting as windbreaks and impeding advection of cooler air from the park.

3.5.2: Variations of PCI intensity and vertical lapse rates over different surfaces

We examined variations in $\Delta T_{u\text{-}p}$ over different heights for both modeled and observed data from surface up to 3 m. Magnitudes of mean PCI were defined as the difference in temperatures between each mean urban (i.e. asphalt, concrete,

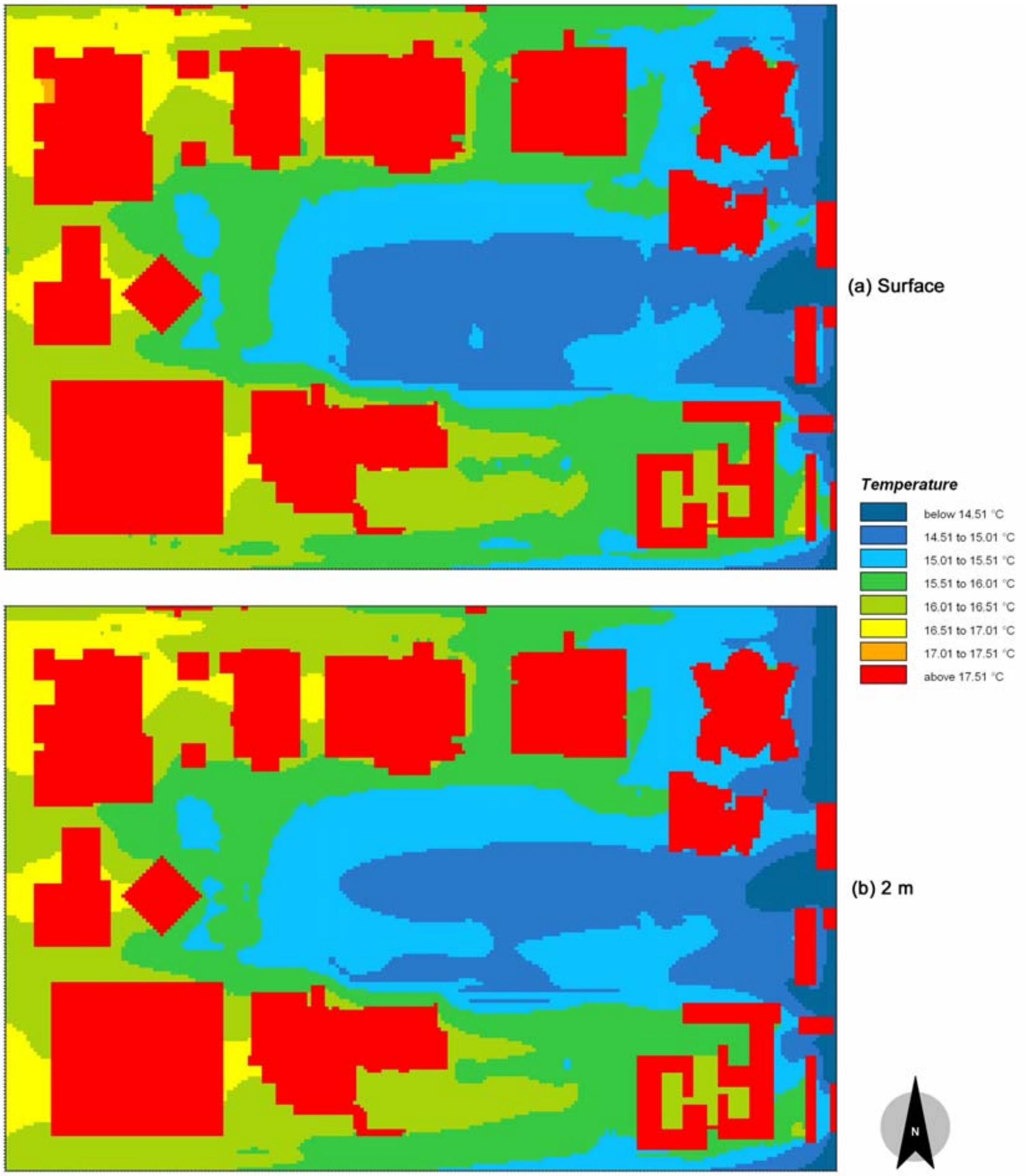

Figure 10: 2-d profiles of ENVI-Met temperature simulations for surface (a) and 2 m levels (b) at 0530 h.

tennis courts and urban canyons) vs. non-urban surface (i.e. lawn or xeric) for all heights (Table 3). Mean observed PCI intensities ranged from 1.4-3.8 °C with magnitudes decreasing significantly with increasing observation height for all surface types. For example, mean $\Delta T_{\text{urban-non-urban}}$, derived by the difference between mean urban and non-urban surfaces, was 2.6 °C less at screen-level heights of 2 m vs. 0.01 m. Mean ENVI-Met PCI intensities were, however, generally lower in magnitude at all comparative heights, especially between the surface and 1 m heights, although qualitative differences (i.e. ranking of PCI intensities between surface types) are largely similar between observed and modeled ΔT_{u-p}.

Different surface types influenced urban vs. non-urban lapse rates. Vertical distribution of mean temperatures measured over asphalt, concrete and within urban canyons showed insignificant changes at all heights (Figure 11); however, similar profiles over tennis court surfaces were generally ~1 °C less compared to other urban surface types. This influences PCI intensity, with $\Delta T_{tennis\ courts-xeric}$ equal to zero at both 2 and 3 m (Table 6). There were also important differences of PCI intensity with respect to non-urban surfaces, as ΔT_{u-p} having consistently greater magnitudes when measured over lawn as opposed to xeric surfaces, with higher intensities documented closer to the ground. Analysis of observed vertical lapse rates showed significant differences of stability between urban and non-urban surfaces. Asphalt, concrete, tennis court and urban canyon surfaces generally had near neutral or slightly stable conditions from 0-2 m, but non-urban xeric and lawn surfaces had a strong inversion observed at those heights, especially from 0-1 m (Figure 11). Above 2 m, however, all surfaces had neutral to slightly unstable air capping the near-surface inversion.

Table 6: Mean PCI (ΔT_{u-p}) over different surface types from observed and modeled data. Heights are measured above surface level (a.s.l.).

	Mean temperature from traverse observations (°C)			
PCI by surface type	*0.01 m*	*1 m*	*2 m*	*3 m*
Concrete – Xeric	2.4	1	0.7	0.5
Concrete – Lawn	3.8	1.3	1.1	0.9
Asphalt – Xeric	2.3	1.1	0.7	0.5
Asphalt – Lawn	3.7	1.4	1.1	0.9
Urban Canyon – Xeric	2.3	1.1	0.7	0.4
Urban Canyon – Lawn	3.7	1.4	1.1	0.8
Tennis Court – Xeric	1.4	0.2	0	0
Tennis Court – Lawn	2.8	0.5	0.4	0.4
Mean Urban – Mean Non-Urban	3.6	1.4	1.0	0.7
	Mean temperature from model simulations (°C)			
PCI by surface type	*0 m*	*1 m*	*2 m*	*3 m*
Concrete – Xeric	0.43	0.37	0.34	0.32
Concrete – Lawn	0.83	0.75	0.70	0.65
Asphalt – Xeric	0.49	0.45	0.41	0.38
Asphalt – Lawn	0.89	0.83	0.77	0.71
Urban Canyon – Xeric	0.78	0.75	0.72	0.70
Urban Canyon – Lawn	1.18	1.13	1.08	1.03
Tennis Court – Xeric	0.15	0.11	0.08	0.05
Tennis Court – Lawn	0.55	0.49	0.44	0.38
Mean Urban – Mean Non-Urban	0.82	0.75	0.70	0.65

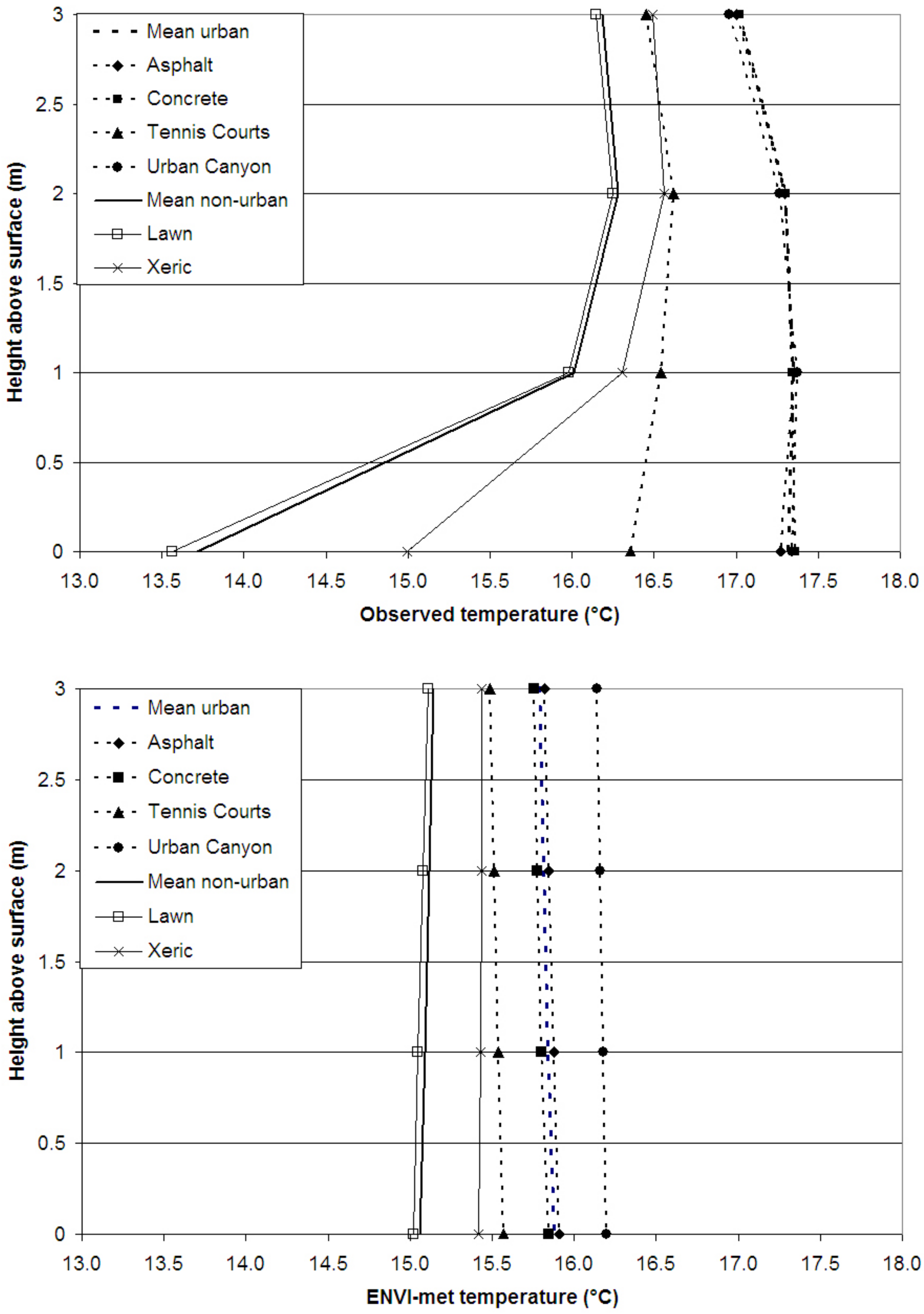

Figure 11: Mean vertical temperature profiles for each surface from traverse data taken at 0.01, 1, 2 and 3 m a.s.l. (top), and corresponding ENVI-Met data at 0, 1, 2, and 3 m a.s.l. (bottom). Urban surface temperatures are the mean profiles of temperatures taken over asphalt, concrete, tennis court and urban canyon surfaces. Non-urban surface temperatures comprise of the mean xeric and lawn profiles.

Modeled lapse rates did not show the stable stratification of observed temperatures; instead, lapse rates were neutral for all surface types from 0-3 m, with a much smaller range especially at lower heights. The order of warmer to colder temperature profiles was largely similar to the observed vertical profiles, with lawn surfaces being coldest and urban canyons being warmest. Of note, however, is that the modeled vertical temperature profile within urban canyons had higher temperatures (0.4 °C) when compared to asphalt or concrete surfaces, whereas such differences in temperature were negligible during the traverse observations.

3.5.3: Evaluation of ENVI-Met simulations

We evaluated the model's performance in terms of accuracy with observed data in two ways. First, modeled spatial temperatures at 0530 h were compared with observed traverse data across similar heights. Second, time series data categorized under different land-use categories at 2 m were averaged and subsequently compared with similar data from the nearby MCAQD Tempe station. In this study, we used several absolute quantitative difference measures of mean bias error (*MBE*), mean average error (*MAE*), root mean square error (*RMSE*) and its derived systematic ($RMSE_S$) and unsystematic ($RMSE_U$) components (Willmott 1982). These error indices, together with the relative, dimensionless difference measure of the index of agreement (*d*) are used in conjunction to evaluate the accuracy of ENVI-Met temperatures, where accuracy is defined as the degree to which predicted observations (*P*) approach magnitudes of actual observed data

(*O*). These measures are preferred to simple correlation measures (e.g. r, r^2) which are completely insensitive to additive and proportional differences that potentially exist between *P* and *O*, and thus may not be consistently related to model prediction accuracy. For instance, it is possible for low or even negative measures of r simultaneously occurring with relatively small differences between magnitudes of *P* and *O*, if the mean of either one of the variables is stationary and its deviations about that mean are unsystematic (Willmott 1984). Further, utilizing difference or error measures allows for evaluation of systematic and unsystematic errors within the model, which are not readily available with simple correlation plots of *P* vs. *O*.

Four model levels corresponding to the nearest traverse sensor height were selected for comparison of spatial temperature fields: 0 m (*P*) with 0.01 m (*O*), 1 m (*P*) with 1 m (*O*), 2 m (*P*) with 2 m (*O*), and 3 m (*P*) with 3 m (*O*) data. The comparison between surface and 0.01 m data may be complicated by observed raised temperature minima over a variety of surfaces (Oke 1970; Geiger et al. 2003), but we assume that these differences are relatively insignificant between 0 and 0.01 m, especially over vegetated areas (e.g. short grass lawns) that have raised active surfaces > 0.01 m generally documented under clear and windless weather conditions (Oke 1987).

The *MBE* for all comparisons show that the model generally under-predicted temperatures by 0.74-1.38 °C (Table 7). *MAE* ranged from 1.16-1.47 °C, with larger error occurring closer to the surface. Magnitudes of *RMSE* for all heights were relatively low (<1.7 °C), but a decomposition of *RMSE* indicates that systematic error predominates. A probable source of this would be the cooler temperatures consistently simulated along the eastern, urban part of the study area (Figure 10), which is in contrast to the warmer temperatures observed during the traverse (Figure 9). A possible explanation could lie in how the model parameterizes lateral boundary conditions for both surfaces and turbulent inflow. The use of open lateral boundaries, coupled with the study area being nested within grids of sandy-loam soils, allows for the constant flow of easterly winds to advect cooler air into the model's eastern boundary. Further, the observed temperature data may be subject to sensor lag in some areas of stagnant turbulence, which affects a key assumption that observed data are error-free in the statistical analysis via difference measures. Another potential error in the observed data could lie with the systematic errors from the spatial join process described in Section 3.4.3, which could propagate additional unavoidable systematic errors. Despite these factors, the relatively low error indices, combined with acceptable magnitudes of *d* (0.4-0.57) given the systematic errors present, suggest that the model reasonably approximates the spatial distribution of temperatures and derived $\Delta T_{u\text{-}p}$.

Time-series data for mean modeled 2 m temperatures over all surfaces compared favorably with 2 m temperature data obtained from the MCAQD Tempe weather station (Figure 12). The model generally under-predicted (over-predicted) nocturnal (daytime) temperatures, which are similar patterns documented in previous applications of ENVI-Met (e.g. Emmanuel and Fernando 2007). During the day, mean temperatures over asphalt surfaces were

Table 7: Difference measures of ENVI-Met model temperatures with observed temperature data at 0530 h.

	Height of ENVI-Met model simulation			
Difference measure (unit)	*Surface*[1]	*1 m*	*2 m*	*3 m*
MBE (°C)	-0.74	-1.33	-1.38	-1.16
MAE (°C)	1.47	1.33	1.38	1.16
RMSE (°C)	1.63	1.50	1.53	1.31
$RMSE_S$ (°C)	1.49	1.32	1.37	1.24
$RMSE_U$ (°C)	0.67	0.71	0.69	0.69
d (Dimensionless)	0.57	0.47	0.41	0.40

[1]: Surface modeled data are compared with observed 0.01m data.

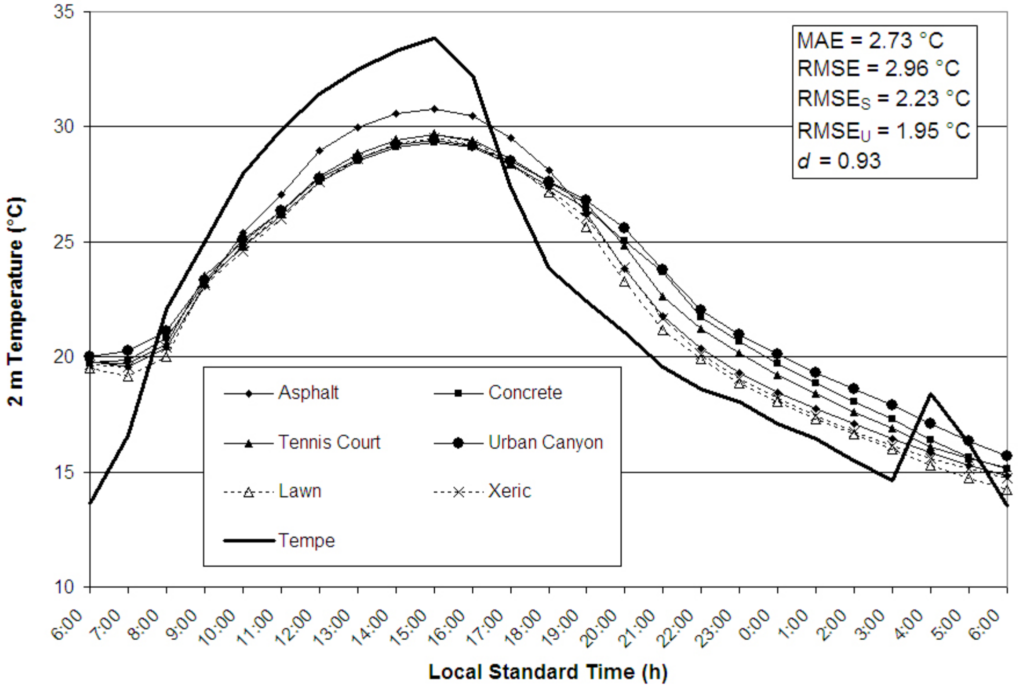

Figure 12: Mean 2 m temperatures from ENVI-Met simulations over different land-use types (see Table 3) and from MCAQD Tempe meteorological station over a 24 h period from Oct 27-28 2007. Difference measures are for mean modeled 2 m temperatures across all surfaces vs. MCAQD 2 m temperatures.

systematically and significantly higher vs. other surfaces, probably due to its larger (lower) heat capacity (heat conductivity) relative to other surface materials. It is also notable that these modeled mean near-surface temperatures over asphalt cooled more than other urban surfaces after sunset. $RMSE_S$ (2.23 °C) was slightly greater than $RMSE_U$ (1.95 °C), which could be a consequence of several limitations of ENVI-Met, such as its inability to (i.) dynamically simulate heat storage for building walls and roofs by having constant building indoor temperatures with no thermal mass, and (ii.) simulate regional-scale thermal and turbulence exchanges that may directly influence micro-scale climates. The latter point can be illustrated with the sudden increase in temperature in the MCAQD data from 0300-0400 h, which could have resulted from advection of warmer air from adjacent urban areas due to the nocturnal near-surface transition (Brazel et al. 2005). Despite these limitations, the relatively low *RMSE* and *MAE*, coupled with the high *d*, suggests that model is accurate in simulating time-series temperature data for this study.

3.6: Discussion

3.6.1: Surface controls on PCI intensity

Compared to results from other studies (e.g. Spronken-Smith and Oke 1998; Jonsson 2004), mean PCI (ΔT_{u-p}) intensities documented in this present study are similar in magnitude i.e. between 0.7-3.6 °C. There are large variations in ΔT_{u-p} between heights, with both observed and modeled PCI intensities being larger at heights closer to the surface (Table 6; Figure 11). Possible explanations for these results are now discussed.

As observations were conducted under mostly ideal meteorological conditions (i.e. clear and mostly calm weather), which largely preclude turbulent transfer of sensible and latent heat fluxes, the large differences of observed temperature magnitudes at 0.01 m heights between urban and non-urban surfaces are probably due to variations of net long-wave radiation losses. These relatively strong upward radiative fluxes occur close to the surface, as seen from the strong temperature gradient between 0-1 m especially over xeric and lawn surfaces (Figure 6). This surface flux divergence probably causes the strong non-urban surface inversions compared to the near-neutral lapse rates observed over urban surfaces.

The radiative losses are controlled by the varying thermal responses of different surface materials, which can be quantified by μ and/or moisture availability. Generally, surfaces with high μ, such as concrete or asphalt, release stored heat at slower rates and would remain warmer at sunrise compared to soil or lawn surfaces (e.g. Oke 1987). Lower temperatures measured over tennis courts could thus be explained by lower μ on this surface. Likewise, differences in 0.01 m temperatures between xeric and lawn surfaces probably arise from μ variations, with lawn surfaces having lower μ values corresponding to lower surface temperatures. Another possible influence, however, would be deviations in non-urban soil moisture content. Two possible impacts on temperature may arise. First, higher (lower) soil moisture results in higher (lower) μ and has been shown to reduce urban vs. non-urban temperature differences (Chow and Roth 2006). Second, given the study area’s arid climate and the strong surface-atmosphere vapor pressure deficit, greater soil moisture would likely result in greater cooling due to increased evapotranspiration, which *a priori* is more likely to occur over lawns than xeric surfaces. The relative importance of these two impacts is unknown and would require further process-based study, although Spronken-Smith and Oke (1999) suggested that cooling from evapotranspiration of soil moisture is more significant pre-sunset, while the additional soil wetness would inhibit nocturnal cooling due to increased μ based on scale and numerical modeling evaluations.

Another possibility explaining variance in urban temperatures could be the relatively larger sky-view factor associated with the exposed tennis courts. The geometry of urban canyons have been shown to influence temperatures and cooling rates with respect to urban parks (Upmanis et al. 1998), and the lack of urban canyons on tennis courts results in unhindered radiative cooling and cooler temperatures. The small but significant variation in modeled ENVI-Met lapse rates between "tennis courts" (which are simulated concrete surfaces) and concrete and urban canyon surfaces (Figure 11) further suggests that changes in urban geometry could be a likely factor in explaining intra-urban temperature differences. However, the lack of significant differences in observed lapse rates within urban canyons vs. exposed concrete and asphalt surfaces implies that the impact of urban geometry on temperatures may be superseded by other larger-scale influences not modeled by ENVI-Met.

3.6.2: Surface/lapse rate relationships and advection

Results from observed lapse rate data in this study are qualitatively similar with the only known previous PCI study that examined vertical temperature differences for urban green-spaces in Stockholm, Sweden (Jansson et al. 2007), with generally neutral/near-neutral (stable) urban (non-urban) profiles observed in both cities. A significant difference lies in the magnitude of profile stability for non-urban surfaces between studies. In Stockholm, the maximum increase in vertical temperatures within a park was ~1.5 °C from 0.47-2.47 m at 22:00 h LT, compared to 2.2 °C (1.4 °C) between 0-3 m for lawn (xeric) surfaces in this study (Figure 11). Variations in green-space type (i.e. lawn/xeric vs. trees), timing of observations (i.e. early evening vs. pre-dawn) and site micro-climates (i.e. different wind speeds and climate types) may help to explain these differences in lapse rate magnitudes. Of more interest is that although the near-neutral vertical lapse rate simulations in ENVI-Met from 1-4 m were qualitatively similar to observed data, the strong stability over lawn and xeric surfaces between 0-1 m was not well modeled, leading to a large under-estimation of simulated $\Delta T_{u\text{-}p}$ within these heights. Whether this is due to inadequate model surface and soil parameterization, or from limitations of modeled surface-atmospheric physics is still unknown and requires further investigation.

The Jansson et al. (2007) study also postulated that advection, possibly generated by pressure gradient from temperature differences between park and non-park surfaces, likely factored in decreases in PCI intensity with height. These local-scale nocturnal "park breezes" of low wind speed (~0.5 ms^{-1}) were observed in Göteborg under clear and calm weather (Eliasson and Upmanis 2000), and could have occurred near the SRC field in this study. Although lower 0.01 m temperatures at tennis courts relative to other urban surfaces were probably due to its different surface characteristics, its low 1-3 m temperatures were likely affected by advection of the cooler air mass from the adjacent SRC field, which can be discerned from Figures 9 and 10. It is very likely that this advection extended the PCI effect westward, possibly by the width of the park itself (~200 m) as suggested by Spronken-Smith and Oke (1998). However, the prevailing easterly winds observed here were similar in direction to the expected E-W evening transition, which affects most of the Phoenix metropolitan area by sunrise (Brazel et al. 2005). It was thus possible that the shift of cooler air over the SRC field during the early morning was driven by this larger-scale synoptic turbulent process, and could have masked potential park breezes. Further PCI observations, especially during the early evening hours during the incipient stages of the evening transition in Phoenix, are needed to determine if park breezes develop in the study area.

3.7: Conclusion

This study investigated the micro-scale impacts of an urban green-space on temperatures located within a hot, arid city. We obtained pre-sunrise temperature data of high spatial and temporal resolution from a bicycle traverse as well as from simulations from a numerical micro-scale climate model (ENVI-Met 3.1). Examination and discussion of horizontal and vertical temperature distributions revealed the following results:

- A strong PCI effect was evident over a large park consisting of irrigated lawn grass and bare soil (xeric) areas. Mean (maximum) observed PCI intensities (i.e. ΔT_{u-p}) were ~3.5 (~6) °C depending on the urban and non-urban surface category, with larger PCI magnitudes documented closer to the surface, especially between 0-1 m heights. Surface type affected PCI intensities, with observed larger ΔT_{u-p} occurring over irrigated lawn as opposed to xeric surfaces, and it is likely that soil moisture and surface thermal properties are likely factors that explain this variance. Urban surfaces more exposed to the atmosphere (i.e. with higher sky-view factors) also had observed lower PCI intensities when compared to surfaces within urban canyons.

- A strong inversion layer was detected over non-urban surfaces, especially between 0-1 m heights, which probably resulted from intense surface radiative cooling from non-urban surfaces. Magnitudes of this near-surface vertical cooling (2.2 °C for lawn surfaces from surface to 1 m) are much greater than reported for a PCI in a high-latitude city (Jansson et al. 2007).
- Spatial and time-series data from the ENVI-Met model were evaluated using a suite of difference measure indices of predicted vs. observed temperatures, which are considered a more preferable statistical method for determining model accuracy as opposed to simple correlation measures. The model reasonably simulated mean spatial temperature fields, especially in areas not directly adjacent to model boundaries that increased systematic errors. However, the model did not simulate the strong near-surface inversion over non-urban surfaces. A comparison with

mean 2 m temperature time-series data at a nearby meteorological station demonstrated a much higher accuracy of mean modeled data, even after accounting for the lack of regional exchange processes that were not simulated in the micro-scale ENVI-Met model.

- Advection of colder park air towards urban surfaces, combined with increased surface exposure to the atmosphere, may be important factors in explaining cooling at different heights over adjacent urban surfaces. Both modeled and observed results showed that the PCI effect at 2-3 m heights over several tennis courts next to the lawn/xeric field was either negligible or non-existent depending on the park surface type. Steady E winds, combined with high sky-view factors at the tennis courts, are probable causes for this result. Urban canyons perpendicular to the prevailing wind had lee effects that manifest as higher observed and modeled temperatures.

Results from this study show that for arid cities, the PCI developed over irrigated lawn and xeric surfaces can be of sufficient magnitude to mitigate the strong UHI in Phoenix, especially within the urban canopy layer (e.g. Brazel et al. 2007). Advection of cooler park air and building orientation also are important factors in variations of PCI over space within the study area; urban planners and builders should be cognizant of these issues when examining how green-spaces can mitigate the UHI. Lastly, although the ENVI-Met model does have relatively larger systematic vs. unsystematic errors, this study shows that its accuracy of observed spatial and time-series data is relatively reasonable, and it has the potential to be utilized as an effective planning tool for modeling micro-scale climates in Phoenix, especially after adapting several vegetation and soil parameters to local conditions

3.8: Acknowledgements

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CHAPTER 4: ASSESSING XERISCAPING AS A SUSTAINABLE HEAT ISLAND MITIGATION APPROACH FOR A DESERT CITY[5]

4.1: Abstract

Metropolitan Phoenix has been amongst the most rapidly urbanizing cities in the USA, and is also subject to an urban heat island (UHI) of significant intensity and extent. There is a need to mitigate its detrimental effects through sustainable methods, such as through the application of low-water, desert-adapted trees with broad canopies within residential yards (i.e. xeriscaping). Urban xeriscaping has the potential to reduce urban water use, urban temperatures and outdoor thermal discomfort in this hot arid city, but evaluating its effectiveness has not been widely researched. In this study, we used a microscale urban climate model (ENVI-Met) to generate xeriscaping scenarios in two different residential areas with different surface vegetation cover (mesic vs. xeric), and subsequently examined the resulting impacts on near-surface temperatures and outdoor thermal comfort over different spatial and temporal scales. Results indicate that low-water use shade trees have strong UHI mitigation potential in existing xeric residential areas in Phoenix, with greater cooling occurring at (i.) microscales (~2.5 °C) vs. local-scales (~1.1 °C), and during (ii.) nocturnal (0500 h) vs. daytime periods (1700 h) under high xeriscaping scenarios compared to base simulations. Conversely, net warming from increased xeriscaping occurred over mesic residential neighborhoods over all spatial scales and temporal periods. These varying results over different residential land cover in Phoenix therefore must be

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[5] This manuscript was co-authored with Anthony J. Brazel and was submitted to *Building and Environment* in February 2011.

considered by stakeholders when considering xeriscaping as a UHI mitigation method.

4.2: Introduction

4.2.1. Urbanization in Phoenix and the heat island

The urbanization process results in a corresponding increase of urban temperatures compared to its rural surroundings. This phenomenon is termed the "Urban Heat Island" (UHI), and is frequently observed for cities in all climate types (e.g. Souch and Grimmond 2006; Roth 2007). Several factors attributed to surface land-use/land cover (LULC) change from urbanization have been hypothesized to explain UHI causation. These include: (i.) increased absorption of short-wave radiation, (ii.) increased storage of sensible heat, (iii.) anthropogenic heat production, (iv.) reduced long-wave radiation losses, (v.) lower evapotranspiration rates, and (vi.) lower sensible heat loss due to reduced turbulence in urban canyons (Oke 1987). Other factors, such as synoptic weather conditions (wind-speed, cloud amount and height), topography, urban morphology, and city size, modify maximum magnitudes of UHI intensity (Arnfield 2003).

The Southwest region of the USA, which includes the states of Nevada, California and Arizona, has experienced the largest rates of urbanization in the country over the past forty years. One example of this rapid urban growth is the large metropolitan area consisting of the city of Phoenix, Arizona, and its associated satellite cities. Metropolitan Phoenix has been among the country's fastest growing urban areas, with population increasing from 1.04 to 4.36 million residents from 1970-2009 (U.S. Census Bureau 2010). This change is also reflected in significant LULC alterations. For instance, ~2553 km^2 of agricultural and desert land underwent conversion to urban surfaces from 1973-2003 (Stefanov et al. 2007), with the majority of development manifest as low-rise suburban residential areas (e.g. Gober 2006). Unsurprisingly, the magnitude of metropolitan Phoenix's UHI intensity, and the size of its spatial extent, has also increased in conjunction with its urbanization (Brazel et al. 2007). Summer UHI intensities can attain magnitudes of ~5 °C between Phoenix and its desert surroundings (Brazel et al. 2000), with largest differences in urban-rural air temperatures often observed at night (Sun et al. 2009).

Although some benefits can arise from increased urban warmth, such as reduced residential heating during winter, UHI impacts in Phoenix have generally been detrimental to society. This applies towards observed biophysical impacts (e.g. thermal discomfort) towards humans and other flora and fauna (Baker et al. 2002), as well as in increased urban demand and use of energy (Golden 2004) and water (Balling and Gober 2007). Due to its hot arid climate, metropolitan Phoenix residents are subject to high daytime physical exposure to heat, as high mean July maximum temperatures regularly exceed 40 °C. A strong nocturnal UHI likely exacerbates this exposure and potentially increases residential vulnerability to heat extremes, especially with limited socio-economic capacity to adapt to such changes (e.g. Turner et al. 2003; Harlan et al. 2006; Chow et al. 2010). Further, increasing vulnerability to extreme temperatures in Phoenix can be compounded by projected climate change impacts in the Southwest U.S., which likely include higher mean temperatures and less precipitation (Christensen et al. 2007).

4.2.2: UHI mitigation – a brief review

One approach to ameliorate the aforementioned detrimental impacts is to implement UHI mitigation strategies with the intention of developing sustainable urban climates (e.g. Mills 2007). These strategies may include methods such as (i.) modifying urban canyon density and street orientation, (ii.) altering thermophysical properties of urban fabric by lowering its thermal inertia, and (iii.) increasing urban vegetation cover and surface shading (e.g. Emmanuel 2005; Sailor and Dietsch 2007; Synnefa et al. 2008; Krayenhoff and Voogt 2010; Yaghoobian et al. 2010). These alter the urban surface energy balance by decreasing net radiation received at the surface, reducing heat storage, and/or increasing latent heat fluxes. Thus, the net effect is the reduction in near-surface sensible heat fluxes (Takebayashi and Moriyama 2007). The physical effectiveness of each method depends on several factors, such as spatial scale (i.e. micro- vs. local- vs. meso-scale) and climate type of the city (e.g. tropical vs. mid-latitude vs. hot arid climates).

Although there is existing arid and semi-arid city research into modifying urban geometry (e.g. Pearlmutter et al. 1999; Fahmy and Sharples 2009) and increasing surface albedo and emissivity (Sailor 1995; Golden and Kaloush 2006), a large body of UHI mitigation research focused on applying urban forestry at various spatial scales (e.g. through urban parks, residential yards or rooftop gardens). This method aims to increase the urban extent of green-spaces and permeable surfaces, through turf grass and/or shade trees. Observational and modeling research have shown that green-spaces significantly reduce surface and air temperatures adjacent to urban surfaces at various spatial and temporal scales (Jauregui 1990/1991; Shashua-Bar and Hoffman 2004; Stabler et al. 2005; Pearlmutter et al. 2007; Shashua-Bar et al. 2009). This occurs through increased evapotranspiration from both vegetation and permeable soils, combined with direct surface-level shading from the vegetation canopy. The cooling influence may also be magnified by larger green-spaces and by increased turbulent transfer of cooler air via advection (Chow et al. 2011). Urban forestry is prevalent in older residential suburbs of Phoenix, where residential landscaping of yards with ample turf grass and large non-native, high water-use shade trees (i.e. mesic landscapes) were used to reduce ambient temperatures before the widespread use of air conditioning (Gober 2006). Urban forests also have other potential physical and social benefits, such as improving air quality, decreasing biodiversity loss, and providing recreational areas for residents (McPherson 2006). Conversely, the effectiveness of urban forestry may be diminished by large amounts of water required for irrigation (Guhathaurktha and Gober 2007), which is of scarce supply in arid cities.

As an UHI mitigation method in Phoenix, urban forestry has been utilized in urban design with the intent of improving its urban sustainability (e.g. City of Phoenix 2008, 2010). The aim is to create microclimates that either accentuate or moderate the properties of the background synoptic-scale climate, as well as to reduce the general profligacy of urban resource use (Mills 2006). Given its climate, the widespread use of water-intensive landscapes in Phoenix, especially in its older residential suburbs, would be contrary to the city's long-term sustainability. Hence, there has been recent focus towards using sustainable UHI mitigation methods, such as the practical use of low-water use plants (i.e. flora adapted to the climate of the Sonoran Desert) in residential yards to replace existing high-water use flora. There is potential in applying this method to both mitigate UHI and reduce urban water use. The importance of this process of "xeriscaping" has been recognized by several cities within metropolitan Phoenix; for instance, the cities of Tempe, Mesa and Glendale have offered financial incentives to homeowners to convert to less water-intensive landscapes in order to reduce water use as well as mitigate high urban temperatures. It could be argued that this method is the most pragmatic option of UHI mitigation when compared to others; for example, there are practical difficulties of maintaining effectiveness of high-albedo surfaces over large spatial scales where dust storms and urban air pollution may reduce albedo over time (e.g. Pio et al. 1998), and it may not be financially feasible for large-scale (re)construction of existing high-density residential areas with new "cool" materials with high thermal inertia.

Previous research on urban forestry in Phoenix examined several of its physical aspects. One study observed micro-scale temperature variations within a small residential study area with respect to variations in surface vegetation. Lower surface and near-surface temperatures were observed over mesic surfaces with ample irrigation when compared to non-mesic surfaces, highlighting the influence of evapotranspirative cooling during summer (Martin 2008). Another study modeled, among other UHI mitigation approaches, the impact of increased vegetation on temperature and thermal comfort in downtown Phoenix. No discernable improvements in thermal comfort using regularly-spaced shade trees when compared to either albedo increases or more dense urban canyons (Emmanuel and Fernando 2007). No simulations of residential areas were attempted in this study, however. Gober et al. (2010) used the LUMPS model (Grimmond and Oke 2002) to test three urban forestry scenarios for 10 census tracts in Phoenix with differing neighborhood types (i.e. industrial, mesic and xeric residential areas). The size of each selected census tract varied from 1-2.6 km^2. Increases in irrigated landscaping were strongly correlated to decreased UHI intensities, but this relationship was non-linear, with greatest (least) reductions in xeric (mesic) neighborhoods. The study, however, did not examine temperature impacts at spatial scales smaller than census tract. One of their scenarios was to replace 10% of combined grass surfaces and trees in modeled neighborhoods with unmanaged soils under conditions of urban water conservation. Although there were significant decreases in evapotranspiration, this scenario resulted in rates of urban cooling decreasing by 0.16-0.39 $°C\ h^{-1}$, which increased UHI intensity for all modeled study areas, especially within xeric neighborhoods. Similar increases in mean cooling rate, and UHI intensity, and urban evapotranspiration were also documented in another modeled xeriscaping scenario (removal of all grass surfaces and increase of unmanaged soil by 20-45 %) that applied LUMPS for 52 census tracts in the city of Phoenix (Middel et al. 2009).

Research hitherto, however, has not examined impacts of xeriscaping on temperatures and thermal comfort within residential areas, especially its explicit influence over different spatial scales (i.e. micro- vs. local) and over different residential surface types (i.e. xeric vs. mesic surfaces). In this study, we thus investigated the effectiveness of xeriscaping on mitigating UHI within two distinct metropolitan Phoenix residential areas. This was accomplished through applying a microscale urban climate model (ENVI-Met 3.1) that was first assessed for accuracy with observed hourly temperature data at meteorological stations located within each study site. Several key model parameters for surface vegetation cover and quantity were subsequently modified for each residential area under different mitigation scenarios. Simulations were also conducted during an extreme heat event (EHE) in Phoenix to coincide with high levels of physical exposure and biophysical discomfort to residents, so as to analyze the potential impacts on temperature and thermal comfort during periods of very high heat exposure. We intend to answer the following questions: (i.) Are there notable differences in near surface temperature and thermal comfort through increasing levels of xeriscaping over different residential areas during an extreme heat event in Phoenix? (ii.) How do the impacts of xeriscaping on air temperatures vary over different spatial scales and temporal periods?

4.3: Methods

4.3.1: Study areas

Table 8: Site characteristics and typical landscaping vegetation.

Study area (LULC category)	No. of housing lots	% lots with grass cover	% lots with at least one shade tree	Typical landscaping vegetation at both study sites (*species name*)
TMP (mesic residential)	129	100%	100%	Bermuda Grass (*cynodon dactylon*) Desert fan palm (*washingtonina filifera*) Mexican fan palm (*washingtonia robusta)* Bottle tree (*brachychiton populneus*) Seville sour orange (*citrus aurantium*) Coolibah (*eucalyptus microtheca*) Shamel ash (*fraxinus uhdei*) European olive (*olea europaea*) Chinese pistache (*pistacia chinensis*) Blue Palo Verde (*parkinsonia florida*)[1] Thornless Mesquite (*prosopis hybrid*)[1]
WPHX (xeric residential)	245	26%	50%	

[1]: Flora selected for xeriscaping scenarios in ENVI-Met.

We selected two suburban residential neighborhoods in metropolitan Phoenix with differing surface land cover characteristics; Tempe (TMP) and West Phoenix (WPHX) (Table 8). Both study areas largely consist of single-story residential houses of similar construction materials (mean roof height $z = \sim 4$ m), but each differ in terms of lot size and land cover. Residential lot sizes in TMP are generally larger (from 1000–2600 m^2) than those in WPHX (~700 m^2), which results in the WPHX study area having more housing lots (245 vs. 129 units respectively). Second, landscaped surfaces in TMP consist of mesic surfaces in the front and back yards of every residential lot, while landscaping in WPHX typically consisted of bare soil and/or gravel mulch, with significantly less lots having landscaping vegetation (Figure 13). Another important distinction between sites is while land cover at the WPHX study area was representative of LULC within the larger-scale residential area, the TMP site was adjacent to a recreational park of substantial size (~8 ha) which had an extensive irrigated turf grass surface. A small portion of this park (~150 x 40 m) included at the SE corner of the study area.

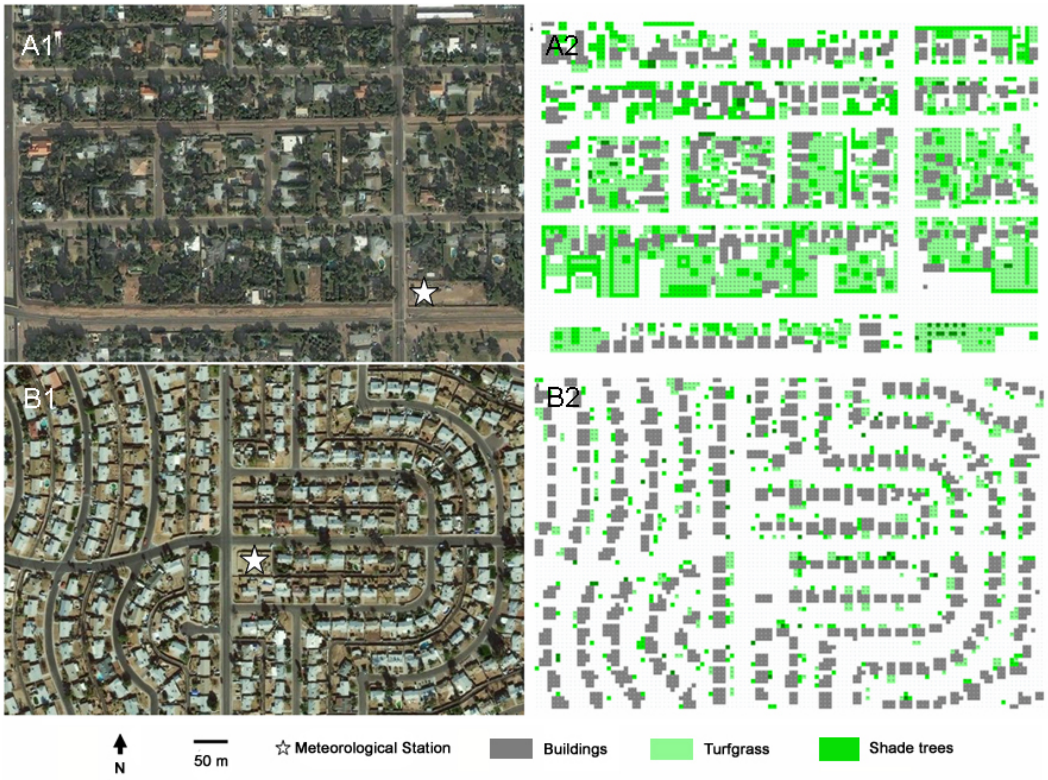

Figure 13: Tempe (A) and West Phoenix (B) study areas. A1 and B1 depict aerial satellite view of study areas, while A2 and B2 are the area input files of the ENVI-Met model environment for Tempe and West Phoenix sites respectively. Note the presence of a recreational park in the SE corner of A1 and A2.

These sites were selected as each represented distinct LULC categories that comprise the vast majority of metropolitan Phoenix land use i.e. either as mesic and xeric residential areas (Stefanov et al. 2007). Each site also lies within census tracts that were classified as highly vulnerable to extreme heat over a ten year period (Chow et al. 2010). Further, both TMP and WPHX each had a meteorological station (that was maintained by the Maricopa County Air Quality Department) within each study area that recorded hourly observations of local near-surface climate data, such as temperature, relative humidity, wind-speed and wind direction.

4.3.2: Urban climate modeling

We applied the ENVI-Met climate model (version 3.1 Beta 5; Bruse 2010) to simulate UHI mitigation scenarios for this study. ENVI-Met is a non-hydrostatic, prognostic three-dimensional numerical model developed from fundamental fluid dynamic and thermodynamic laws, which allows for micro- and local-scale modeling of soil, surface, building and vegetation interactions with the atmosphere within the urban canopy layer (Bruse and Fleer 1998). This model has been widely used in research into urban climatology, building design and planning (e.g. Ali-Toudert and Mayer 2006; Emmanuel and Fernando 2007)

ENVI-Met simulations require an area input file that specifies three-dimensional geometry of the study area, and this includes building dimensions (e.g. width and height), soil (e.g. type and texture), surface (e.g. concrete or asphalt) and vegetation types (Figure 13). In this study, we applied an improved vegetation parameterization scheme over the model defaults that included leaf area densities of typical flora observed in local residential landscapes in metropolitan Phoenix (Chow et al. 2011). The size of each individual model grid cell was selected to match the neighborhood spatial scale (5 x 5 x 2 m), and the total model environment size was 128 x 78 x 30 cells for both TMP and WPHX. The model environment was also nested within five nesting grids with the predominant soil type of each neighborhood for improved numerical stability during model runs. ENVI-Met simulations also require a local configuration file containing local soil, meteorological and building input data for model initialization at each study area (Table 9). These include (i.) 2 m above surface level (a.s.l.) temperature and relative humidity, (ii.) 10 m a.s.l. wind speed and direction, (iii.) specific humidity at 2500 m a.s.l,, (iv.) soil temperature and relative humidity, and (v.) building interior temperatures, mean heat transmission (i.e. thermal conductivity divided by mean wall or roof width), and mean albedo values for roofs and walls. These data were obtained from meteorological stations within each study area, from the NCEP/NCAR reanalysis project at the NOAA/ESRL Physical Sciences Division (NOAA 2010), from existing datasets listing typical thermophysical properties of typical building materials (e.g. Oke, 1987), and from field reconnaissance within both study areas.

All model simulations were run for 24 h, with updated surface data every 60 s., starting from sunrise (0500 h) during July 4-5 2007. This period was selected as it occurred during the middle of an EHE from July 3-6 2007 as defined by criteria set by Meehl and Tebaldi (2004). Highest observed maximum and

Table 9: Selected input parameters for ENVI-Met base simulations at TMP and WPHX study areas.

Category	User input during simulations	
Meteorological inputs	*TMP*	*WPHX*
Wind speed and direction 10m a.s.l.	1 m s^{-1}/90°	1.5 m s^{-1}/ 230°
Mean roughness length of study area	0.35 m	0.3 m
Specific humidity at 2500 m a.s.l.	3 g kg^{-1}	3 g kg^{-1}
Relative humidity at 2 m a.s.l.	24 %	20 %
Initial atmospheric temperature[1]	301 K	305 K
Soil inputs		
Initial soil temperature at upper layer (0-20 cm)	304 K	306 K
Initial soil temperature at middle layer (20-50 cm)	305 K	307 K
Initial soil temperature at lower layer (below 50 cm)	306 K	308 K
Relative humidity upper layer	35 %	20 %
Relative humidity middle layer	40 %	25 %
Relative humidity lower layer	45 %	30 %
Building inputs		
Building interior temperature	298 K	298 K
Mean heat transmission[2] of walls	1.94 W m^{-2} K^{-1}	1.94 W m^{-2} K^{-1}
Mean heat transmission of roofs	6 W m^{-2} K^{-1}	6 W m^{-2} K^{-1}
Mean wall albedo	0.4	0.4
Mean roof albedo	0.5	0.5

[1]: This is the mean air mass temperature assumed to be more or less independent from surface layer processes for the duration of the simulation (M. Bruse, pers. comm.). Site parameters were estimated as an average value of T_{2m} data over 24 h.
[2]: Estimated thermal conductivity of building material (W m^{-1} K^{-1}) divided by mean wall thickness (m).

minimum temperatures at National Weather Service's Sky Harbor Airport meteorological station were 46.7 and 33.9 °C respectively during this EHE (Grossman-Clarke et al. 2010). From the simulations, we obtained the spatial distribution of potential temperatures throughout the model environment, which were subsequently converted to absolute near surface (2 m a.s.l.) temperatures (T_{2m}) through Poisson's equation. We used T_{2m} data in our analysis as direct comparisons with meteorological station data at each study area could be made for model evaluation. We specifically focused on temperature data taken at 5 p.m. and 5 a.m. local time (LT), which corresponded to approximate summer maximum and minimum temperatures in Phoenix. Modeled mean radiant temperatures (MRT) at 2 m. a.s.l. were also analyzed to quantify outdoor thermal comfort. We decided on using MRT as it is the most important meteorological input parameter when deriving the human energy balance, especially during summer conditions, and it has the greatest influence on other thermophysiological indices like Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET) (Matzarakis et al. 2007).

4.3.3: UHI mitigation scenarios

In this study, we selected three distinct xeriscaping scenarios for each study site. Model outputs from each scenario were compared with base simulations with existing land and vegetation parameters. We focused on simulated conversion of mesic landscape treatments at both TMP and WPHX to desert-adapted, low-water use flora. We followed xeriscaping guidelines suggested by the City of Mesa (2010), which offered financial rebates for homeowners to convert previous mesic surface cover in both front and back yards to at least 50% xeric cover. In our simulations, selected residential lots had half of its previous yard surface left as bare soil/ground, and the other half replaced with low-water xeric shade trees. We thus selected the Blue Palo Verde (*parkinsonia florida*) and Thornless Mesquite (*prosopis hybrid*) trees in our study. These vegetation species have been parameterized for ENVI-Met simulations based on observed leaf area density (LAD) measurements of mature trees in Chow et al. (2011), and these data were applied in our simulations. While other desert-adapted plants could have been selected, these have limited direct shade potential to alter microclimates. Both selected species have broad canopies when mature, and typically require significantly less total irrigation than mesic residential shade trees.

Table 10: Xeriscaping conversion scenarios and alterations to model parameters.

Scenario	Selection method of houses undergoing conversion	Alterations to model parameters	Number of lots undergoing xeriscaping	
			TMP	*WPHX*
Low (10%)	Random assignment throughout model environment	Front and back yard surfaces of individual residential lots replaced with 50% bare soil and 50% mature Blue Palo Verde (7.5 m) and Thornless Mesquite (9 m) trees	13	25
Medium (25%)			32	61
High (50%)	Alternate assignment (i.e. chessboard pattern)		65	123

We selected three xeriscaping scenarios for each site (Table 10); low (where 10% of selected residential housing lots at each site undergo conversion to xeric vegetation), medium (25%) and high (50%). We first calculated the number of lots that would undergo landscaping conversion in each case. For the low and medium scenarios, we randomly selected housing lots throughout each study area for the conversion process. Given the incentive options from cities in metropolitan Phoenix, we argue that a random selection pattern is more likely to occur in reality as opposed to a systematic selection process, such as designated xeriscaping “zones” within the study area. For the high xeriscaping scenario, however, every alternate house in both study areas was selected for conversion akin to a “chessboard” pattern. Given the prior literature, we expected that our xeriscaping scenarios would result in contrasting impacts in our study areas; higher and lower mean temperatures at TMP and WPHX respectively.

4.4: Results

4.4.1: Model evaluation

Hourly T_{2m} data from both meteorological stations in TMP and WPHX were compared with mean modeled T_{2m} throughout the model environment (Figure 14). WPHX mostly observed higher temperatures throughout most of the 24 h period, peaking at 45.1 °C at 1700 h LT. The ameliorative impact of greater surface vegetation within TMP was apparent in lower temperatures observed throughout most of the day. This was especially apparent during the nocturnal period, with minimum temperatures at 0500 h LT being 25.3 °C, compared to 31.1 °C at WPHX. We compared this with mean ensemble T_{2m} taken over all model surfaces during each ENVI-Met base simulation at TMP and WPHX. The model generally underestimated daytime T_{2m} and overestimated nighttime T_{2m} at both sites. This feature was also apparent in previous applications of this model in Phoenix (Emmanuel and Fernando 2007; Chow et al. 2011).

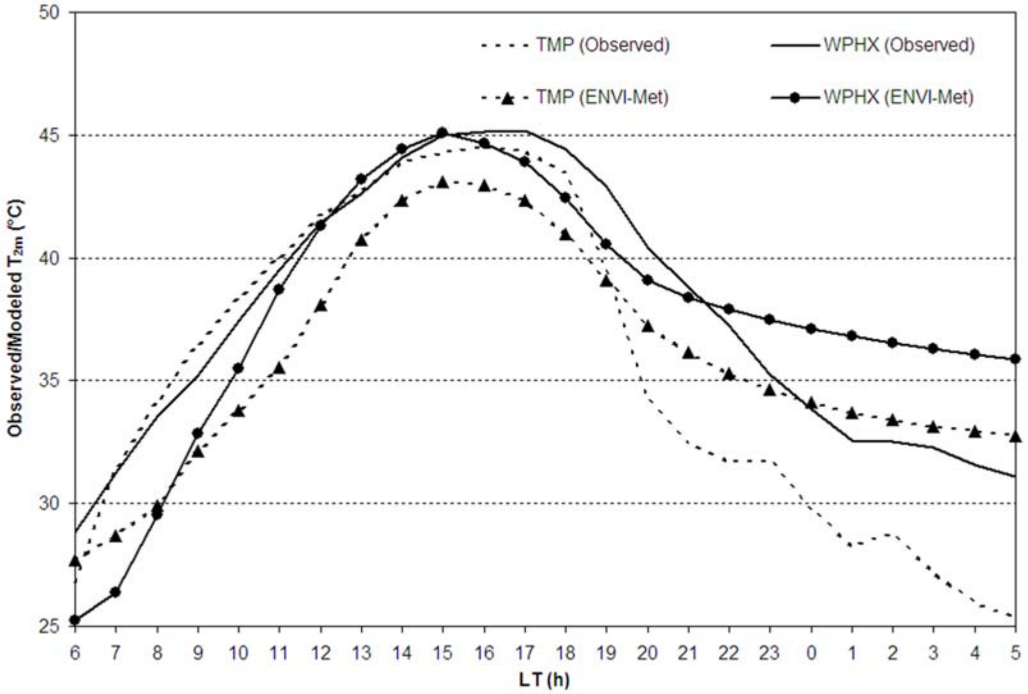

Figure 14: Comparison between observed hourly near-surface temperatures (T_{2m}) from July 4-5 2007 taken at both TMP and WPHX meteorological stations with mean ensemble T_{2m} from ENVI-Met simulations for each study area.

We evaluated the accuracy of predicted ENVI-Met (*P*) with observed time-series temperatures (*O*) using both correlation (i.e. r^2) and difference measures (i.e. *RMSE*) (Figure 15), where accuracy is defined as the degree to which magnitudes of *P* approaches magnitudes of *O*. The suite of difference measures used include the mean bias error (*MBE*), mean absolute error (*MAE*), root mean square error (*RMSE*) and its derived systematic ($RMSE_S$) and unsystematic ($RMSE_U$) components, and the index of agreement (*d*) (Willmott 1982). Even with the underestimation (overestimation) of peak daytime (nighttime) temperatures, modeled T_{2m} data showed generally good agreement with observed meteorological station data at both sites, which was apparent with both correlation ($r^2 > 0.67$) and difference indices ($d > 0.86$).

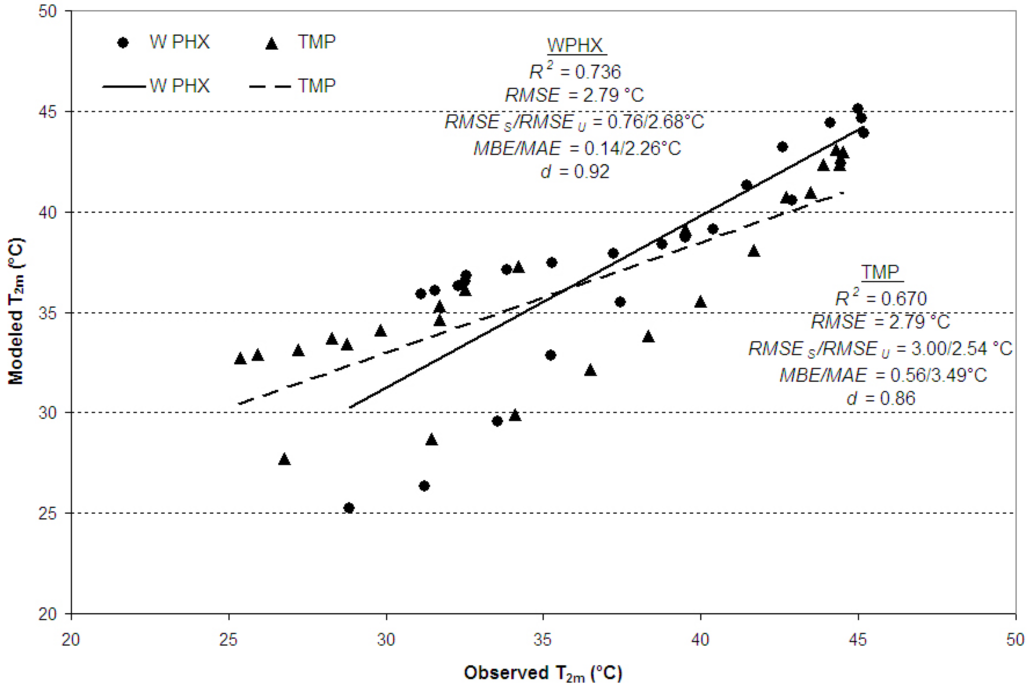

Figure 15: Evaluation of observed vs. modeled T_{2m} time-series data from Figure 14. R^2 = coefficient of determination; *RMSE* = root mean squared error; $RMSE_S$ = systematic *RMSE*; $RMSE_U$ = unsystematic *RMSE*; *MBE* = mean bias error; *MAE* = mean absolute error; *d* = index of agreement.

Despite several known flaws inherent in ENVI-Met, such as (i.) the inability to dynamically simulate meso-scale thermal and turbulence exchanges that potentially influence micro-scale climates, and (ii.) the oversimplification of building facades with a single mean heat transmission value for all houses within the model environment, modeled T_{2m} data showed acceptably low magnitudes of *MBE*, *MAE* and *RMSE*. This suggested that the model design of base scenarios were largely accurate. There was, however, a notable exception with $RMSE_S > RMSE_U$ at TMP, possibly indicating inaccurate parameterization of this site. This could be explained by the influence of the large recreational park adjacent to the SE of the study area. It has been postulated that the source area of urban temperature sensors extends to a circle of ~500 m radius around the instrument (Oke 2006a). This would include the dimensions of the entire park, which is not included in the ENVI-Met model scenarios. In contrast, the source area of the WPHX sensor would not include dissimilar LULC types from its modeled environment. In our estimation, this factor likely accounted for the systematic error in the TMP model. Nonetheless, the high r^2 and d indicates that our model parameterization would be suitable for the study's objectives.

4.4.2: Temperature/thermal comfort differences between xeriscaping scenarios

We plotted differences in 24 h local-scale ensemble T_{2m} (ΔT_{2m}) between all xeriscaping scenarios with the base model parameters from both TMP and WPHX (Figure 16). This would describe variations to local-scale temperatures at both sites. Despite the minor alterations in green-space, mean impacts to T_{2m} arising from the low and medium xeriscaping scenarios were discernable at both sites. Low and medium xeriscaping scenarios in TMP showed marginal increases in warming during the day (approximately +0.2 °C), but increases in ΔT_{2m} magnitude were slightly larger at night, especially in the medium scenario (approximately +0.35 °C). In WPHX, however, low and medium xeriscaping scenarios resulted in mean local-scale decreases in ΔT_{2m} by -0.1 and -0.3 °C respectively. In contrast, larger variations in mean ΔT_{2m} were observed for high xeriscaping scenarios at both study sites. At TMP, local-scale increases of mean ΔT_{2m} in late afternoon temperatures were about +0.8 °C, with further nocturnal increases in excess of +1 °C. Conversely, local-scale ΔT_{2m} at WPHX were consistently lower by around -0.7 °C for most of the simulation, with little slightly larger observed nocturnal cooling of ΔT_{2m} (-0.75 vs. -0.65 °C) compared to daytime magnitudes.

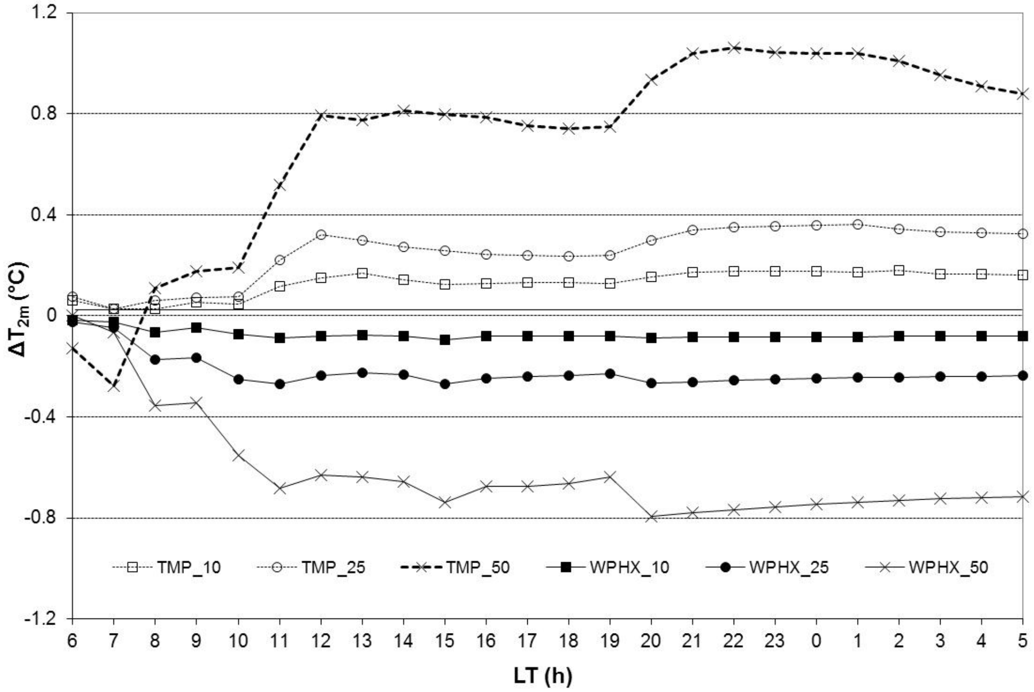

Figure 16: Difference (ΔT) between T_{2m} time-series data from base simulations with modeled ensemble mean T_{2m} from all UHI mitigation scenarios. The suffix "10" = low xeriscaping (surface conversion of 10%); "25" = medium xeriscaping (25%); "50" = high xeriscaping (50%) for both TMP and WPHX study areas.

We subsequently compared and examined the impact of xeriscaping over micro- and local-spatial scales by plotting ΔT_{2m} maps between base and all three xeriscaping scenarios during approximate maximum (1700 h) and minimum (0500 h) temperature timings for TMP (Figure 17) and WPHX (Figure 18) respectively. Magnitudes of microscale (i.e. at the spatial scale of individual

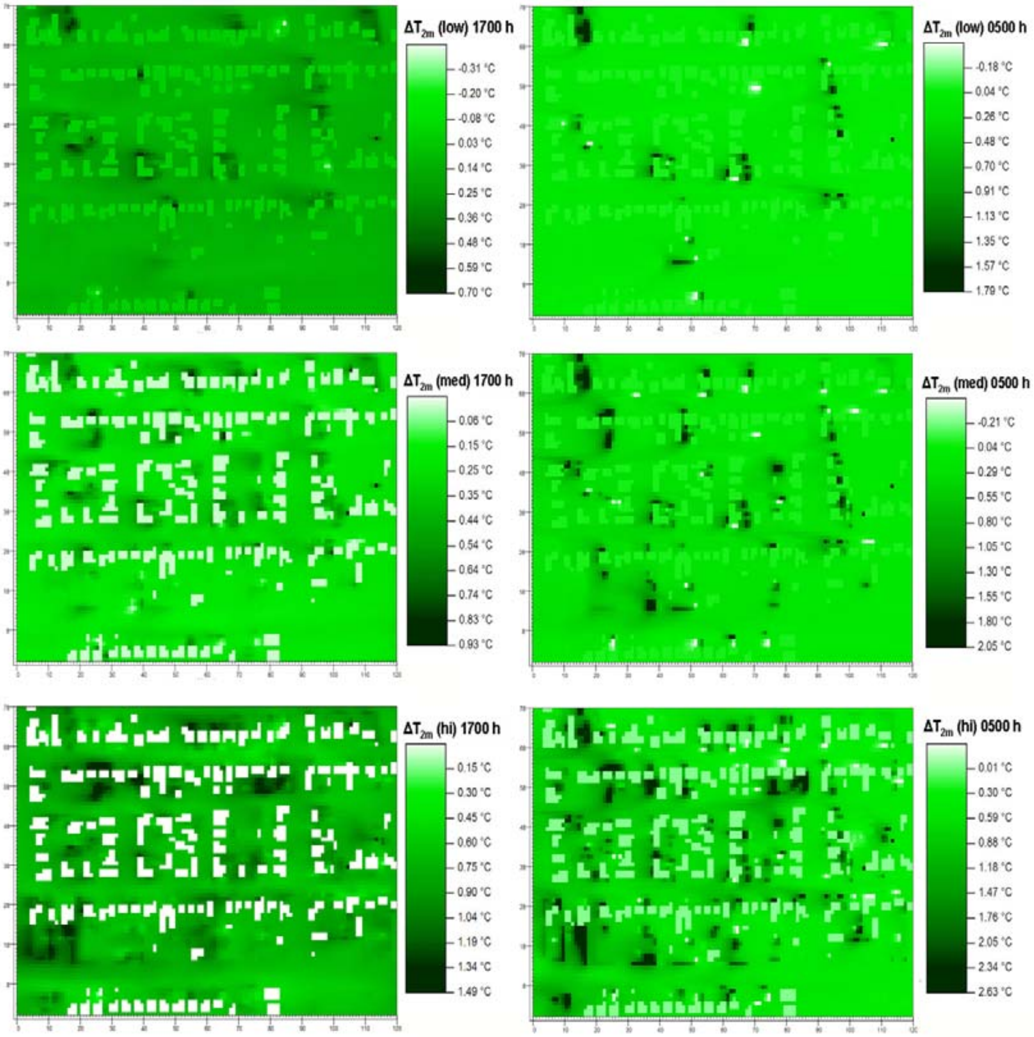

Figure 17: Difference plots of 2 m a.s.l. temperatures (ΔT_{2m}) between base simulations and modeled scenarios in TMP for low (top), medium (middle) and high (bottom) xeriscaping respectively during 1700 h (left) and 0500 h LT (right).

residential lots) warming in TMP are significantly larger than at local scales (i.e. the background model environment). There was a notable pattern of maximum warming magnitudes increasing with higher xeriscaping scenarios, with larger ΔT_{2m} increases observed at 0500 h compared to 1700 h (e.g. +2.6 °C vs. +1.5 °C under the high xeriscaping scenario). Conversely, significantly lower microscale

ΔT_{2m} were observed at WPHX. The pattern of maximum cooling magnitudes with higher xeriscaping was also mirrored, with greater nocturnal vs. daytime cooling

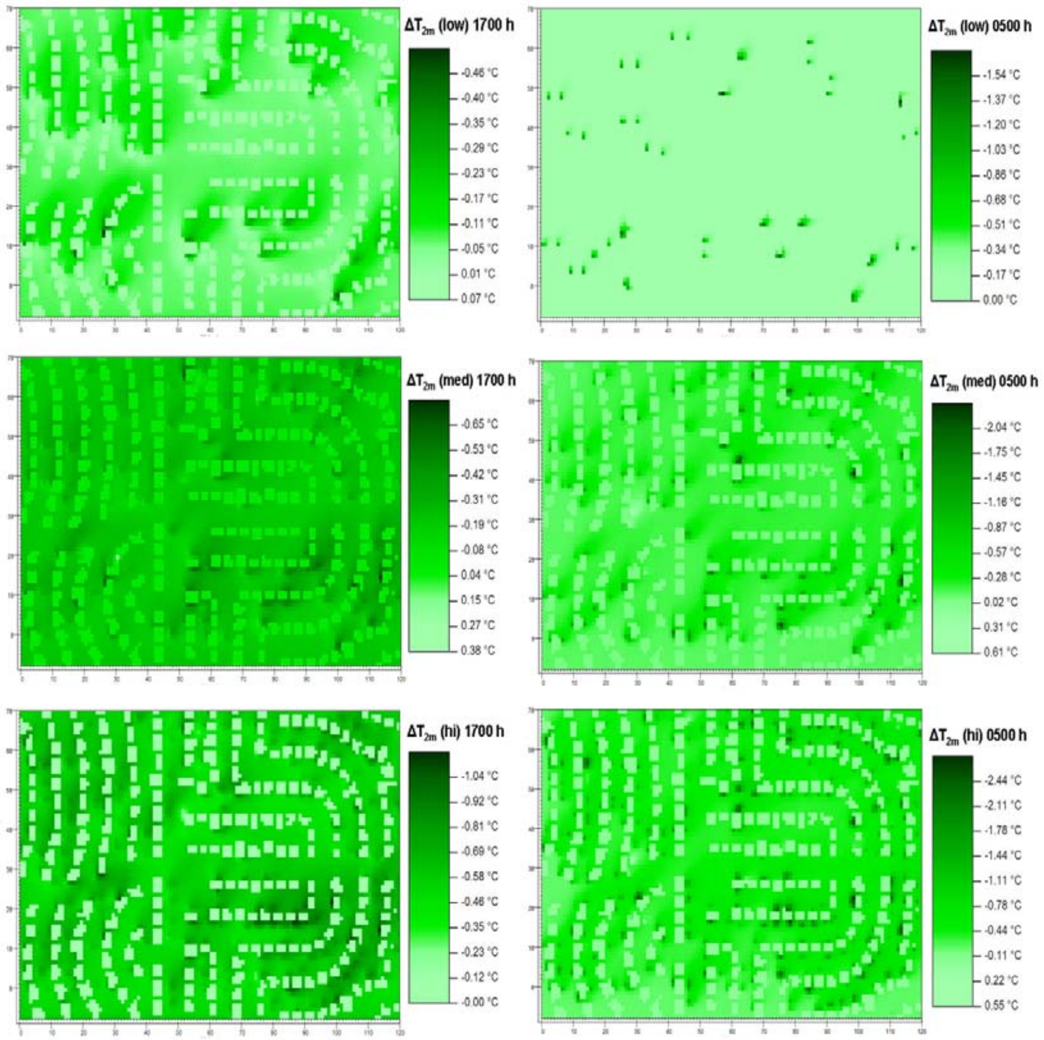

Figure 18: Same as Figure 17 but for WPHX.

(e.g. -2.4 vs. -1 °C under the high xeriscaping scenario) The ΔT_{2m} maps at both sites also reveal the distinctive "patchy" microscale pockets of warming or cooling that is limited to the individual residential lot and adjacent houses, especially in low xeriscaping scenarios at both sites. Lastly, it is notable that the least variation of ΔT_{2m} in TMP was in the SE corner of the study area, which is part of the recreational park.

Advection and near-surface turbulence appears to influence the spatial variation of temperatures at both sites. During the simulations, the predominant mean wind direction was from the E and SW at TMP and WPHX respectively (Table 9). At TMP, easterly advection likely resulted in the notable expansion of higher T_{2m} towards the west, especially at 0500 h. This advective pattern was also apparent in WPHX, which observed SW winds shifting cooler temperatures towards NE of the model environment. The influence of advection is also notable when examined under scenarios of increasing xeriscaping, as the pockets of cooler/warmer microscale patches correspondingly expand and affect more unconverted residential lots that were located further away (e.g. between 20-50 m or 3-4 lots in WPHX and 50-75 m or 6-8 lots in TMP). Near-surface atmospheric stability could also be a factor in explaining temperature variations between 1700 and 0500 h; unstable and stable conditions could affect micro- and local-scale turbulence during maximum and minimum temperature periods respectively.

Table 11: Average simulated mean radiant temperature (MRT) for all modeled UHI mitigation scenarios during 1700 h and 0500 h LT.

Mean Radiant Temperature (°C)			
TMP at 1700 h LT (and at 0500 h LT)			
Base	Low (10%)	Medium (25%)	High (50%)
75.5 (22.1)	79.6 (26.2)	80.4 (26.3)	84.9 (26.9)
WPHX at 1700 h LT (and at 0500 h LT)			
Base	Low (10%)	Medium (25%)	High (50%)
92.4 (30.6)	90.2 (30.5)	87.9 (30.3)	86.3 (30.1)

Lastly, we examined outdoor thermal comfort using 2 m a.s.l. mean radiant temperature (MRT) that were derived from model outputs at 1700 h and 0500 h LT (Table 11). It is apparent that daytime MRT magnitudes reflect the extreme discomfort during the EHE in Phoenix for both residential areas. Similar daytime and nocturnal MRT magnitudes were also reported in summer observations taken within the desert city of Beni-Isguen, Algeria (Ali-Toudert et al. 2005). Notable variations in MRT existed between sites, however. Generally, the higher T_{2m} in WPHX, combined with less surface evapotranspiration from fewer mesic surfaces, corresponded in substantially higher daytime (92.4 °C) and nighttime (30.6 °C) magnitudes of MRT and resulting thermal discomfort when compared to TMP (75.5 and 22.1 °C respectively). There was also a correspondingly distinct increase (decrease) in MRT at TMP (WPHX) with greater xeriscaping at each site, especially during maximum temperature conditions. For instance, the high scenario resulted in a change of mean MRT at TMP by +9.4 °C and +4.8 °C at 1700 and 0500 h respectively; conversely, the high scenario at WPHX observed -6.1 °C (1700 h) and -0.5 °C (0500 h).

4.5: Discussion

As with most modeling studies, there are several caveats that have to be considered before discussing its results. Firstly, we acknowledge that the xeriscaping modeling scenarios selected are simplified, especially when compared to observed xeriscaping in metropolitan Phoenix neighborhoods. Residential xeric landscaping can include a multitude of low-water use flora with different canopy types and size, which include various cacti and desert shrubs species such as the Saguaro (*carnegiea gigantea*) and Creosote bush (*larrea tridentata*) respectively. We did not obtain ENVI-Met vegetation parameterizations for these xerophytic species, which was a factor in their omission in this study. Further, we were guided by recommendations in the City of Phoenix's (2010) Tree and Shade Master Plan, which suggested the use of shade trees (such as the Thornless Mesquite and Blue Palo Verde) in order to improve levels of urban shade canopy. Another caveat is the presence of the recreational park in the TMP study area that could have influenced the relatively high $RMSE_S$ mentioned in Section 3.1. This was unavoidable, given the need for a representative residential study area that had a local meteorological station that enabled model evaluation. It is possible that this would result further underestimation of temperatures relative to those simulated in the model, and it is something to consider when transposing these results to other mesic neighborhoods that may not be adjacent to a large park with its cooling influence on temperatures and thermal comfort.

Despite these limitations, a key result from this study is the encouraging potential for xeriscaping with shade trees as a UHI mitigation method, especially within dry/xeric residential areas in Phoenix. The increased shading and transpiration from the broad canopy of the selected xeric trees at WPHX have distinct daytime and nighttime cooling impacts. The effectiveness of cooling also varies between spatial scales. Magnitudes of cooling are markedly larger at microscales (i.e. the residential lot and adjacent buildings), with potential maximum nocturnal cooling ranging from 1.5–2.4 °C in areas immediately adjacent to the shade trees. Magnitudes of cooling are substantially less at larger, local spatial scales, but these impacts are still discernable, especially at higher levels of xeriscaping. On the other hand, the impacts of xeriscaping on temperatures and thermal comfort clearly differ between residential LULC categories, as the removal of water-intensive surfaces and trees consequently increased temperatures in the mesic residential area at TMP. These considerable temperature increases are likely due to decreased evapotranspiration and shade. Likewise, changes in outdoor thermal comfort quantified by MRT in each scenario mirrored the variations in temperatures at both TMP and WPHX. Increasing levels of xeriscaping conversion (i.e. from low to high) also resulted in greater variations in the magnitude of MRT at both sites, possibly from the addition or removal of shade trees that block direct insolation at WPHX and TMP respectively.

This cooling potential of low-water use shade trees is an important consideration for sustainable UHI approaches in Phoenix, especially as previous xeriscaping model simulations with LUMPS only accounted for turf grass removal (Middel et al. 2009, Gober et al. 2010), but not the addition of spatially explicit vegetation at micro- or local spatial scales. The placement and careful management of these shade trees are therefore essential in not only reducing near-surface temperatures in xeric residential neighborhoods, but also improving outdoor thermal comfort through shade for pedestrians under conditions of extreme daytime temperatures. Further, the dynamic influence of advection and near-surface turbulence was not considered in previous xeriscaping studies. In this study, advection is potentially important in expanding the microscale cooling influence in the xeric residential neighborhood, possibly through the turbulent mixing of cooler air that integrates cool microscale “patches” over a larger area. This spatial expansion of cooling from advection is further magnified with higher levels of xeriscaping at WPHX, further highlighting the utility of this method in mitigating UHI when widely applied.

Lastly, these results suggest that proposed xeriscaping methods in Phoenix, and possibly in other arid cities, should include low-water shade trees to reduce UHI intensities, especially within xeric residential areas. With the majority of residential areas in metropolitan Phoenix classified as xeric surfaces in a recent categorization of urban LULC of the city (Buyantuyev 2005), widespread xeriscaping with shade trees could potentially be effective in reducing UHI intensities at a large scale whilst conserving water. However, as with the aforementioned studies in Phoenix, a reduction in quantity of vegetation in mesic residential areas likely results in a net increase in near-surface temperatures across spatial scales, which increase in magnitude with greater conversion. Thus, large-scale residential xeriscaping in other neighborhoods similar to TMP may result in greater thermal discomfort to residents. Lower levels of xeriscaping may lead to only marginal increases in local-scale neighborhood temperatures, but the detriment of projected warming have to be evaluated against the potential water savings from the elimination of water-intensive residential vegetation. The analysis of this tradeoff between microclimate cooling vs. neighborhood water use, however, is beyond the scope of this study.

4.6: Conclusion

To summarize, this study examined the impact of xeriscaping on temperatures and thermal comfort at micro- and local spatial scales within two different residential neighborhoods in metropolitan Phoenix through the ENVI-Met microscale climate model. Several scenarios were proposed – low, medium and high xeriscaping – in which existing surface vegetation and soil cover in residential yards were altered with the addition of desert-adapted shade trees and conversion to bare soils to minimize water use in this arid city. The results indicate that impacts of xeriscaping on temperatures strongly depend on the LULC categorization of the residential area. The removal of water-intensive, non-native plants and turf in mesic residential areas results in a net increase of temperatures and additional thermal discomfort across spatial scales. Conversely, xeric residential areas observed notable decreases in temperature and improvements in outdoor thermal comfort with more low-water use shade trees at both micro- and local-scales. Greater magnitudes of temperature variations were documented at microscales compared to local scales under all modeling scenarios, with small, patchy pockets of cooling/warming within individual residential lots and their adjacent buildings. Modeled advection also influenced the integration of these microscale pockets, and greatly expanded neighborhood warming/cooling with increasing xeriscaping and atmospheric stability. The potential of xeriscaping with low-water shade trees in mitigating UHI is thus apparent, especially in xeric residential areas.

This study's results have also shown the importance of considering spatial scale differences with modeling urban climates and the UHI. Indeed, a possible future avenue of study could be to compare the local-scale results from ENVI-Met with other local-scale urban climate models, such as LUMPS, TEB (Masson 2000) or SLUCM (Kusaka and Kimura 2004) to possibly evaluate inter-model performance. It is therefore important for stakeholders interested in modifying urban climates (e.g. planners, scientists and policy makers) to acknowledge that no single model developed for a specific spatial and temporal resolution can provide a comprehensive tool to evaluate possible UHI mitigation scenarios or other aspects of urban climate. There could be some utility, however, in analyzing projected urban climates by using a combination of urban climate models applied across different scales, if these are properly evaluated with observed data.

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CHAPTER 5: CONCLUSION

5.1 Summary of dissertation results

Chapter 2 evaluated the broad extent of peer-reviewed literature on UHI research within metropolitan Phoenix, and discerned three major themes across different spatial scales: (i.) theoretical contributions from study of UHI physical characteristics; (ii.) inter-disciplinary investigation into its biophysical and social consequences, and; (iii.) subsequent research into, and policy implementation of sustainable UHI mitigation and adaptation techniques. There were several important factors intrinsic to Phoenix that helped facilitate UHI research; (i.) a high-quality, long-standing network of urban meteorological stations allowing for relatively fine spatial resolution of near-surface temperature data; (ii.) strong applied urban climate research partnerships developed between several agencies, such as the academy, the National Weather Service, private energy firms and municipal governments, and; (iii.) a high level of public and media interest towards the UHI that manifest in numerous newspaper articles and broadcast media reports.

Chapter 3 examined the horizontal and vertical impacts of a small park on nocturnal near-surface temperatures at micro- and local-scales though a mobile traverse, and through simulations with the ENVI-Met 3.1 model. An improved vegetation parameterization scheme based on observed LAD data from several typical landscaping vegetation species used within Phoenix was also developed to improve on the default model scheme. A distinct PCI of close to 4 °C was detected, with larger magnitudes of cooling closer to the surface from both direct traverse observations and model simulations. Modeled results possessed varying but generally reasonable accuracy in simulating both spatial and temporal temperature data, although some systematic errors were present. Several factors, such as variations in surface thermal properties, urban geometry, building orientation, and soil moisture were likely responsible for influencing differential urban and non-urban temperatures. A strong inversion layer up to 1 m over vegetated surfaces was detected, contrasting with near-neutral lapse rates over urban surfaces. The expansion of PCI was also influenced by advection of cooler park air to adjacent urban surfaces, although this effect was mostly concentrated from 0-1 m heights over urban surfaces that were more exposed to the atmosphere.

Chapter 4 applied ENVI-Met 3.1 to generate xeriscaping scenarios in two residential areas with differing surface vegetation cover (mesic vs. xeric), and examined the resulting impacts on near-surface temperatures and outdoor thermal comfort over different spatial and temporal scales. The model utilized the improved vegetation scheme tested in Chapter 3, and were evaluated with hourly temperatures from meteorological stations within each study area. Generally, the model showed high magnitudes of accuracy with observed temperatures taken at similar heights based on both correlation and difference statistics. The results suggested that the use of desert-adapted low-water use shade trees has strong UHI mitigation potential in existing xeric residential areas in Phoenix. Greater cooling magnitudes occurred at (i.) microscales (~2.5 °C) vs. local-scales (~1.1 °C), and during (ii.) nocturnal (0500 h) vs. daytime periods (1700 h) under high xeriscaping scenarios when compared to base simulations. On the other hand, net warming from increased xeriscaping occurred over mesic residential neighborhoods over all spatial scales and temporal periods. These results suggest a need for further evaluation of urban climate models in simulating mitigation scenarios across different spatial scales.

5.2 Contribution to academic knowledge

In conclusion, each dissertation chapter has provided new contributions to existing UHI knowledge, as well as towards the field of urban climatology. First, the literature review highlighted how the long history of extensive UHI research in metropolitan Phoenix has been important in developing new insights into this phenomenon, especially with respect to knowledge in rapidly developing cities in similar climates. It also emphasized the important factors, both from intrinsic and extrinsic sources, which drove research in the city and made it a unique case for the study of UHI. Furthermore, the knowledge attained from almost 90 years of research into its physical form and impacts has translated into policy into sustainable UHI mitigation in several cities within metropolitan Phoenix. The methods and approaches used here to develop sustainable urban climates could also be a useful guide to interested policymakers and researchers in other cities.

Second, the PCI study revealed new insights into both vertical temperature lapse rates of urban vs. non-urban surfaces in an arid city, as well as on the influence of advection in expanding PCI extent over non-urban surfaces. These issues have not been extensively observed or modeled in previous research. The widely-used ENVI-Met model was also adapted for use in Phoenix with an new vegetation scheme that improved model accuracy. This scheme utilized LAD data observed from typical vegetation species used in residential landscaping in Phoenix, and it could be applied by future users of ENVI-Met in this city.

Third, the xeriscaping scenarios tested in the last study highlighted the intriguing potential of desert-adapted, low-water use shade trees in mitigating UHI, especially within xeric residential areas that comprise a significant portion of metropolitan Phoenix's land area. It is among the first urban climate studies to examine the explicit impact of these vegetation species on near-surface temperatures and outdoor thermal comfort over differing spatial and temporal scales. The study also suggests that this approach may not be effective in mesic residential areas, with the caveat that possible trade-offs between residential water use and thermal comfort from UHI mitigation have not been evaluated yet. Lastly, further investigation of spatial scale variations between urban climate models for UHI mitigation scenarios is also recommended.

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APPENDIX A

STATEMENT OF PERMISSION

I declare that I have obtained explicit permission from my co-authors for including three peer-reviewed scientific journal manuscripts as chapters in this dissertation. They are:

- Anthony J. Brazel (Chapters 2, 3 and 4);
- Chris A. Martin (Chapter 3) and;
- Ronald L. Pope (Chapter 3).

Winston T.L. Chow
February 25th 2011.