OPTIMIZING THE EFFECT OF VEGETATION FOR PEDESTRIAN THERMAL COMFORT AND URBAN HEAT ISLAND MITIGATION IN A HOT ARID URBAN ENVIRONMENT

Akram Rosheidat[1], Harvey Bryan[2]
1. Ph.D. Student, School of Architecture + Landscape Architecture, Arizona State University, Tempe, AZ, USA.
2. Professor School of Architecture + Landscape Architecture, Arizona State University, Tempe, AZ, USA.

ABSTRACT

Rapid urbanization in Phoenix, Arizona has increased the nighttime temperature by 5°C, and the average daily temperatures by 3.1°C. The energy balance of urban surface paving materials is the main contributor to the phenomenon of the Urban Heat Island effect (UHI). Much of the literature dealing with mitigating UHI effects recommends extensive tree planting as the chief strategy for reducing the UHI. However, while the extensive tree canopy is beneficial in providing daytime shade for pedestrians, it may reduce the pavement surfaces' sky-view factor during the night, thereby reducing the rate of nighttime radiation to the sky. From a UHI mitigation perspective, it may be more beneficial to use low height vegetation that does not reduce the sky view factor as large shade trees would, increasing the urban surfaces' nighttime radiation potential. This paper proposes to use field data and simulation scenarios to optimize the use of vegetation for both improving daytime pedestrian thermal comfort as well as enhancing nighttime radiation. The CFD microscale and mesoscale urban scenarios simulation results can potentially give urban planners and architects insights on improving their recommendations for implementing landscape design strategies for optimal effect on both the pedestrian scale and larger urban forms.

INTRODUCTION

The city of Phoenix has been growing rapidly in the last few decades. It is now larger than Los Angeles, California in land area. The metro area is composed of a number of Cities and Towns which are connected through a network of highways. Buildings and paved surfaces in urbanized areas now absorb and reradiate much more heat than the original natural desert landscapes they replaced. Taha et al. (1992) demonstrates that as a result, pavements and building roofs become 27-39°C hotter than the ambient temperature. This in turn affects and raises the ambient temperature through sensible, latent and radiative heat flow exchanges (Asaeda 1996). The temperature of the urban areas can be in the range of 1.11-4.44°C higher than the surrounding natural landscape (Oke 1987).

In typical natural desert settings, the ground heats up during the day but it releases the heat during the night. Desert climates worldwide are known to have a significantly large diurnal temperature range resulting in cold nights even in the summer, as the stored heat in the desert soil is all radiated back to the clear desert sky (Olgyay 1963). However, once the natural desert is built up with high heat storage absorbing materials such as asphalt and concrete, this natural balance is upset. Today, in the desert of Phoenix, Arizona satellite thermal imagery show road/highways and parking lot pavement surfaces having the highest night time surface temperatures (Golden 2004). Akbari et al. (1999) states approximately 39% of the urban area canopy is made up of paved surfaces, including parking lots and sidewalks. Since these surfaces make up the vast majority of the urban fabric, and are the main culprit in causing the Urban Heat Island effect, it is essential to understand the mechanism by which they influence the near surface air temperature, and their role in the increasing of the temperatures in the urban areas.

URBAN SURFACE ENERGY BALANCE:

As the sun strikes surfaces on earth and heats them up, these surfaces start interacting with the air layer above them and exchange heat and energy. The extent of this exchange is dependent on the physical properties of the surface being irradiated. These properties include thickness, color and roughness, thermal conductivity, specific heat capacity, density, moisture content, and emissivity. As the surface is irradiated and heats up, it stores the heat, and when the surface of the material becomes hotter than the ambient temperature, it starts interacting with and raising the adjacent ambient temperature through sensible, latent and radiative heat flow exchanges (Olgyay 1963, Asaeda 1996). Per Asaeda et al. (1996) most of the infrared radiation emitted from ground surfaces is absorbed within 200m (±620 feet) of the lower atmosphere, having a significant effect on the air temperature near the ground. Typically, in the lower atmosphere, infrared radiation emitted by the ground surface is almost equal to the downward radiation from the atmosphere when there is only a relatively small difference between the air and ground surface temperatures. However, once the ground surface temperature is raised significantly above the air temperature, the infrared radiation from the ground surface increases, and is absorbed by the air above the surface. At noon for example, when the difference between air and ground surface temperature is large, the rate of infrared absorption by the lower atmosphere over asphalt pavement was greater by 60 Wm^{-2} than that over the soil surface or concrete pavement (Asaeda et al. 1996).

RURAL SETTING:

The rural setting around Phoenix is characterized by either native desert land or agricultural fields surrounding the urban area. Agriculture uses extensive irrigation, and therefore the soil would have much higher moisture content than the native landscape. The irrigated agricultural land in the past had a cooling effect on the air temperature because of the latent heat exchange with the air above it. However, since the agricultural land has been gradually replaced by urban growth, the general ambient air temperatures have been steadily climbing.

Bare soil has poor reflectivity and therefore a large portion of the incoming solar radiation is absorbed. Due to latent heat exchange in the soil surface, its surface temperature stays relatively cooler and its longwave radiation is smaller when compared with urban pavement surfaces. Because of the soil surface characteristics, its surface heats up slower than concrete and even slower than asphalt during the day (Doll et al. 1985, Asaeda et al. 1993). Even though the temperature of the soil surface is lower than that of concrete, the overall sensible heat flux is much larger. The heat stored below the soil surface during the day is comparable to the amount stored by concrete. However, soon after sunset, the soil surface cools down to the ambient air temperature much faster. Due to the soil's poor conductivity, the deep soil layers do not absorb as much energy. This cooling effect is also aided by latent heat exchange through evaporation of moisture, not just at the soil's surface, but inside the soil as well. Once the top layer moisture is evaporated, there is an upward transfer from deeper soil layers to the surface, and subsequent evaporation. So the soil releases its heat to the atmosphere via sensible, latent and radiative heat exchange mechanisms (Asaeda et al. 1993). The result is that at night, the soil surface temperature is lower than the temperature of the air above it. Thus, it does not contribute to the heating of the night air. This is unlike the asphaltic and concrete surfaces whose surface temperature stays higher than the surrounding air during the night, and into the early morning, continuously heating the air above them through sensible heat exchange and radiation, due to their large heat storage capacity and lack of latent heat exchange (Asaeda et al. 1996, Doll et al. 1985, Chalfoun 1991).

EFFECT ON UHI IN THE URBAN CONTEXT OF PHOENIX, ARIZONA:

In various studies impervious concrete and asphalt surfaces can reach surface temperatures of 50–56°C in the summer (Pomerantz et al. 2000). As these surfaces store heat during the day, and reach capacity down to the subsurface, at night, this energy is released as convective and radiative heat (Nunez and Oke 1977, Oke 1981, Nakamura and Oke 1988). This is an effect of the night time radiation; cooling of these surfaces by radiating stored heat through the exchange with the night sky. This process is therefore directly related to the sky view factor and the proportions of the street or urban space. The color and roughness of the urban materials also have an impact on how much energy they absorb, and therefore re-radiate. Surfaces that have a high albedo, typically light colors and smooth surfaces, reduce the heat storage in the materials (Doll et al. 1985, Akbari et al. 1995, Taha et al. 1997). However increasing the albedo alone of these surfaces was not found to be the most significant factor in controlling the surface temperature aspects; rather, the heat storage capacity and section thickness were determined as more important factors in the heating and cooling of surface pavements (Golden 2006, Emmanuel and Fernando 2007). Asaeda et al. research in 1993 also indicated that allowing latent heat exchange plays a major role on cooling pavement materials. The asphalt and concrete used in urban environments is typically too dense to allow water permeability and therefore drastically limits the latent heat exchange. Current research at the ASU Smart Lab indicates a great potential for pervious pavements. As opposed to typical asphalt and concrete pavements, pervious pavement is permeable to water and air and therefore allows for a latent heat exchange. These pavements can be made out of asphalt or concrete, but contain less fines. This works in a multitude of dimensions; for instance, it decreases the street storm water runoff by absorbing the storm water and recharging underground aquifers. The water and air passage allows latent heat exchange, and therefore decreases the temperature of the pavement. This in turn assists trees and other landscape root systems to better access air and nutrients, providing cooler root zones which result in larger and denser shading landscape materials (Golden 2007).

IMPACT ON HUMAN COMFORT AND AIR QUALITY:

The greatest heat gain of the pedestrian walking or standing in the urban environment is from radiation. This is primarily from direct solar radiation if the person is standing in direct sunlight. However, assuming the person is standing under a shade structure or a tree, eliminating the direct radiation effect, the second main heat gain factor is the long wave radiation emitted from the surrounding irradiated materials. Past research in this environment has repeatedly confirmed the dominant role of the Mean Radiant Temperature (MRT) in the human energy balance (Bryan 2001). Comparatively, the heat gain of the pedestrian, as a result of the air's ambient temperature via convection, is relatively minor. Therefore, the primary goal should be controlling the radiant temperatures of the surface materials that impact pedestrians in this fashion. Daytime field measurements in the summer in Phoenix, Arizona show horizontal and vertical material surface temperatures that can climb up to 65°C. These surfaces are typically within six to eight feet from the pedestrians, and can have a substantial effect on their thermal comfort (Bryan 2001).

PROPOSED UHI MITIGATION STRATEGIES:

Increasing the urban vegetation has been cited in numerous publications as one of the most effective strategies to accomplish UHI mitigation (McPherson et al. 1994, Akbari et al. 1995, Taha et al. 1997). According to Akbari et al. 2001, urban tree planting, combined with increasing the surface albedo citywide, has the potential of modifying the entire City's energy balance. Additionally, the trees' evapotranspiration, or the latent process involving evaporation of water at the stomata of the tree leaves, as well as water trapped in the soil, is sometimes cited as a microclimate modification strategy (McPherson and Simpson 1995). However, in an urban setting, and in terms of UHI mitigation, the scale of the cooling caused by evapotranspiration is insignificant due to the rapid dissipation of any "cooler air" through air turbulence in a hot summer street. Evapotranspiration is effective only in situations where significant irrigation occurs such as in agricultural fields or watered grass lawns. In an urban context, the effect of the vegetation is dependent on the amount of the planted area as related to the urban built-up area. It is also dependent on the size and location of the trees, specifically on the tree's LAI (leaf area index) and LAD (leaf area density), which are indicators of the tree's shading potential. When we consider large vegetated areas such as parks, studies show that the cooling can affect even the surrounding areas. However, in their research, Shashua-Bar and Hoffman (2000) studied the tempering effects of shade trees at small urban vegetated sites. They concluded whatever the cooling effect resulted (in their case 1-3°C), was mainly (80%) attributable to the shading effect of the tree as opposed to other factors. They concluded that for hot climates, the most effective use of the vegetation is its shading property which reduces the direct solar radiation incident on the high heat capacity materials of the street.

However, the main cause of the UHI problem remains the urban horizontal surface pavement material. These horizontal surfaces cool down at night as a factor of their sky view. Therefore, having a thick tree canopy cover may reduce the rate by which these surfaces lose their stored heat. If the goal is to reduce the temperature and heat storage capacity of the urban surfaces, then the composition of the urban surfaces should be targeted to emulate natural surfaces (e.g. green cover, bare soil) as much as possible.

The urban tree canopy, depending on its size, height, and density, plays a role in shading the surfaces and decreasing their surface temperature and heat gain compared with the exposed surfaces.

Researchers at the Lawrence Berkeley National Laboratory have published extensively on the quantification of the benefit of trees and vegetation as related to outdoor comfort, energy savings, and impact on the Urban Heat Island (Taha et al. 1996, Rosenfeld et. al. 1998). In one of the analysis papers on strategies for mitigating the urban heat island in Los Angeles, their data shows that the L.A. UHI can be reduced by as much as 3°C through the use of high albedo roofs, pavements and urban forestation. To achieve this though, the urban forestation has to consist of planting an additional 11 million trees in Los Angeles (Rosenfeld et. al. 1998). However, this data does not show whether the tests/simulations took into account the reduced sky view factor as a result of this immense proposed urban tree canopy. If the goal is to lower the nighttime surface temperatures and reduce its negative effects, then further study has to be done on optimizing the size and density of the proposed green canopy. The simulation/experiment this paper will test is the relationship and optimization of the various site variables, such as the vegetation type, height and density, and type of urban surface materials with varying sky view factors; to ascertain maximizing the reduction of nighttime urban surface temperatures, and thereby reducing the urban UHI effect.

METHODOLOGY:

The goal of this study is to simulate MRT and surface temperatures of various urban surfaces of hypothetical scenarios using various combinations of urban surfaces and densities, with various sizes, densities and configuration of vegetation in the urban environment of Phoenix, Arizona (33° 27’ N, 112° 04’W, 1,117 feet above sea level). The results are intended to help optimize proposed guidelines for reducing the urban surfaces’ daytime heat gain and increasing radiation to the night sky.

Surface temperature data was collected at various sites in downtown Phoenix. Collection of data was done in series of sessions between May 2007 and September 2007. The climate stations collected the following data: dry-bulb temperature, relative humidity, solar radiation, wind speed, and globe temperature. Vertical and horizontal surface temperatures were collected using an infrared thermal gun. The sky view factors were recorded and quantified by means of fish-eye photography.

Numerical simulation models are advantageous when testing UHI mitigation scenarios as opposed to field measurements. Using these models allows testing various potential scenarios relatively fast making them preferred tools in urban climatology (Arnfield 2003). The ENVI-met software, developed by Dr. Michael Bruse of the Environmental Modelling Group Institute of Geography at the University of Mainz in Germany, has been assessed in past literature as a micro-scale simulation model with fine temporal resolutions, and one of the only micro-scale computational fluid dynamic models capable of analyzing human thermal comfort in an urban environment with a robust vegetation heat exchange capabilities, and resolutions as detailed as 0.5m x 0.5 m (Bruse 2010).

The ENVI-met software uses input values for buildings, vegetation, ground surfaces, climatic conditions, soils, and then simulates the modifications from the proposed building form, additional shading, alternative orientations, etc. ENVI-met is a three-dimensional computer model which analyzes micro-scale thermal interactions within urban environments. The software uses both the calculation of fluid dynamics characteristics, such as air flow and turbulence, as well as the thermodynamic processes taking place at the ground surface, at walls, at roofs and at plants. ENVI-met takes into account all types of solar radiation (direct, reflected and diffused) and calculates the surface temperatures as well as mean radiant temperature. The calculation of radiative fluxes includes the plant shading, absorption and shielding of radiation as well as the re-radiation from other plant layers (Bruse 2007). In calculating MRT, ENVI-met takes into account all radiation fluxes, direct, diffuse and reflected solar radiation as well as the long-wave radiation fluxes from the atmosphere, ground and walls and is capable of producing MRT values for each cell of the model environment at varying heights above the ground surface (Toudert 2005, Emmanuel & Fernando 2007).

ENVI-met, however, has certain limitations. The tools to create the urban environment are limited to buildings, soils/pavement materials and trees/vegetation. There are no tools to create any other objects, such as shade structures independent of the building blocks. Furthermore, the albedo and thermal resistance of the building surfaces is constant and cannot be varied (Emmanuel & Fernando 2007).

There are many examples in related literature validating the ENVI-met model outputs (Lahme, Bruce 2003, Emmanuel and Fernando 2007) concluding that ENVI-met reproduces measured data with adequate accuracy and is a dependable tool in simulating various urban scenarios. In this paper, the goal is to compare the relative effects of separate UHI mitigation scenarios for the horizontal urban surfaces of a hypothetical urban downtown site in Phoenix, Arizona. Therefore, the ENVI-met results are a useful benchmarks despite the limitations mentioned above.

SIMULATION:

To asses the optimization of the commonly suggested scenarios for UHI mitigation related to the urban surface temperatures, the simulation will test the following scenarios:

- Scenario 1: Baseline: bare soil, exposed, no vegetation, shaded by building shape/geometry of urban space only. Sky view factor in the center of the space ±0.96.
- Scenario 2: Entire space covered with irrigated grass, exposed, no other vegetation or trees, shaded by building shape/geometry of urban space only. Sky view factor in the center of the space ±0.96.
- Scenario 3: 4” thick concrete pavement, exposed, no vegetation, shaded by building shape/geometry of urban space only. Sky view factor in the center of the space ±0.96.
- Scenario 4: 4” thick concrete pavement, shaded with dense large trees (30’ diameter crown) and building shape/geometry of urban space. Sky view factor in the center of the space ±0.36.
- Scenario 5: 4” thick concrete pavement, shaded with low density smaller trees (15’ diameter crown) and building shape/geometry of urban space. Sky view factor in the center of the space ±0.96 (vegetation/trees at perimeter with a sky view factor of ±0.71).
- Scenario 6: 4” thick concrete pavement, shaded with low density low height (3’ high maximum) vegetation hedges and building shape/geometry of urban space. Sky view factor in the center of the space ±0.96 (around vegetation areas with a sky view factor of ±0.80).
- Scenario 7: low density porous concrete pavement, shaded with dense large trees (30’ diameter crown) and building shape/geometry of urban space. Sky view factor in the center of the space ±0.36.

RESULTS AND DISCUSSION:

Figure (1) shows the values of the surface temperatures as simulated by ENVI-met at 6:00 pm (highest diurnal surface temperature) and 6:00 am (lowest diurnal surface temperature).

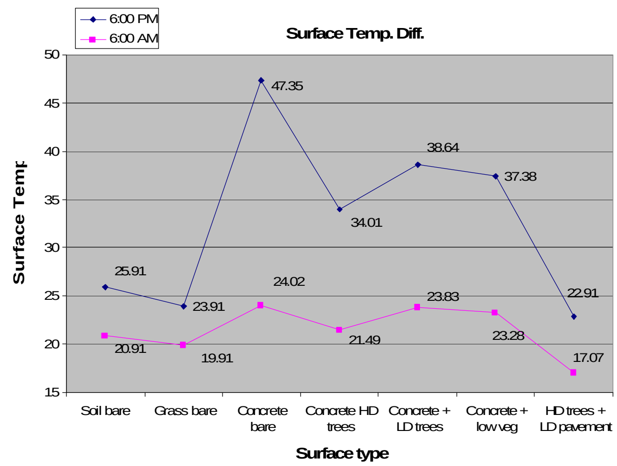

Figure (1): Simulated surface temperatures at 6:00 am and 6:00 pm, Phoenix, Arizona.

Without the use of any shading, the surface with the lowest daytime and nighttime surface temperatures is irrigated grass lawns. Using this surface mimics the rural setting in Phoenix Arizona in the recent past, which was made up largely of irrigated agricultural fields. Without any additional shading, the simulated surface temperatures of the irrigated grass lawn were 23.91°C at the hottest point during the daytime and 19.91°C in the early morning.

As expected, the worst surface performance was the bare unshaded concrete pavement which, despite the fact it had the largest swing in surface temperature between daytime and early morning (• 23.33°C), remained as the hottest surface in the early morning hours at 24.02°C.

With the additional vegetative tree canopy shading, the best test result was for the low density porous concrete covered with a dense tree canopy. In this scenario, both the daytime (22.91°C) as well as the early morning temperature (17.07°C) were the lowest of all the cases tested. This works better than simply raising the albedo of urban pavements, as increasing the albedo alone was not found to be the determinative factor in controlling the surface temperatures.

In the four scenarios using standard concrete pavement (the preferred and ubiquitous urban pavement material) the data shows the most favorable scenario is shading the pavement with a dense tree canopy. This reduces the storage and heat absorption of the concrete significantly. For standard concrete pavement, covering it with shade appears to be a more important strategy, despite the fact it reduces its sky view factor. Figure 2 shows that in the early morning, the surface directly under the tree canopy is slightly warmer (by ±2.78°C); however the average surface temperature is lower than any of the other standard concrete pavement scenarios (Figure 1).

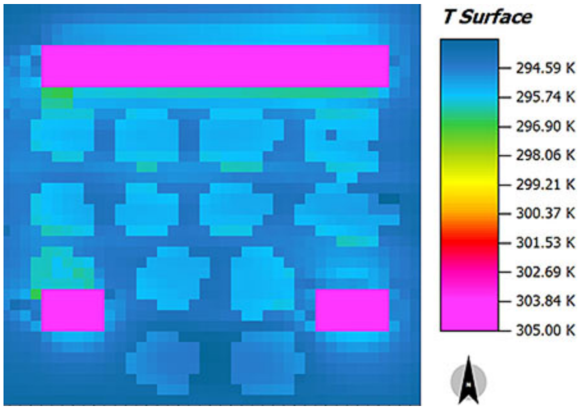

Figure (2): Concrete pavement with high density tree canopy (large distribution high LAD) shading

Comparing the other two standard concrete scenarios, one with low density trees and the other with vegetation lower than 3 ft, the results show these two scenarios are close in terms of surface temperature. However, the scenario with vegetation lower than 3 ft does a little better (by ±0.56°C) cooler both at 6:00 pm and at 6:00 am. Both these scenarios allow significant irradiation of the surface compared to the dense tree canopy scenario. However, the low vegetation case has a larger sky view factor (±0.80) as opposed to (±0.71) for the low density tree case which could account for the lower morning surface temperature.

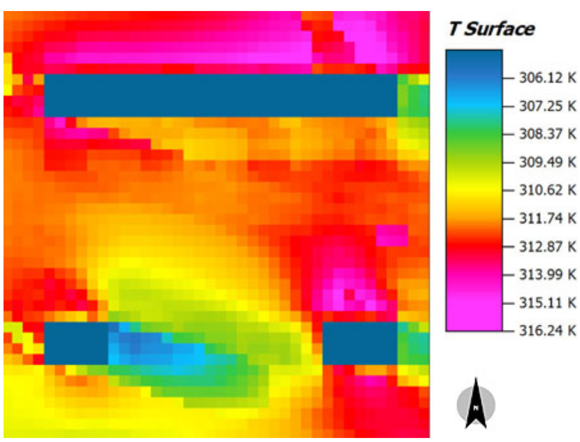

Figure (3): Concrete pavement with low density tree canopy (perimeter distribution low LAD) shading

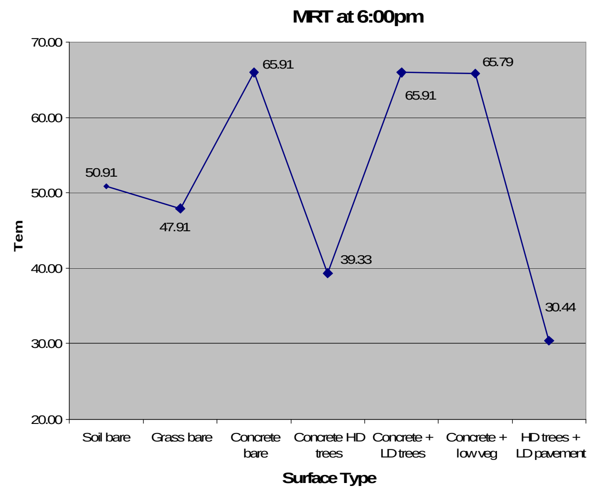

Figure (4): Simulated mean radiant temperature (MRT) by surface type at 6:00 pm in Phoenix, Arizona.

In terms of human comfort, the pattern of the mean radiant temperature (MRT) follows the surface temperature pattern. Figure 4 above shows the importance of shading strategies as the best scenarios shown are when using shading with a dense tree canopy. However, the best value is for the combination of the dense tree canopy with the low density porous pavement (MRT = 30.44°C).

CONCLUSIONS

Both for mitigating the UHI and for outdoor human comfort, it is essential to provide shade and to decrease the temperature of the surfaces emitting longwave radiation. The results show that the primary target for UHI mitigation should be the material properties of the horizontal urban surfaces as they form the preponderance of the surface area of the urban fabric. The data indicate that merely recommending massive tree planting in urban areas may not abate the UHI effect as much as addressing the combination of shading using trees and surface materials choices. The role of the material and thickness of the urban surfaces has a primary role in the increased temperature of cities. Additionally, the surface temperature of urban landscape is the primary factor in the decreased human thermal comfort as it is the main contributor to the mean radiant temperature. Irrigation (moisture) enhances the cooling effect by adding latent heat exchange. However, the scarcity of water resources in an already dry climate dictates a careful balance between using water extensively for reducing urban surface temperatures.

The solution therefore should be in finding an optimal balance between surface materials properties combined with the height, density and quantity of trees/vegetation used. The focus of future work should be on managing and optimizing the introduction of additional shade and cooling effects via increasing the tree canopy cover, and replacing high density, high heat capacity surfaces like concrete paving with lower density porous pavement materials. These two strategies are symbiotic in that the porous pavement, especially in parking lots and around vegetation, results in larger shading landscape materials. Low density, low conductivity porous pavement materials mimic the natural desert terrain, and by allowing latent heat exchange, can play a major role on cooling urban surfaces.

ACKNOWLEDGMENT

The assistance of the following is gratefully acknowledged: Mr. Saravanan Balasubramanian and Professor Daniel Hoffman for their review and assistance with the data collection during the summer of 2007.

REFERENCES

Akbari H., Rosenfeld A.H., Taha H. (1995) Cool Construction Materials Offer Energy Saving and Help Reduce Smog. ASTM Standardization News 23, 11: 32 -37.

Akbari, H., Rose, L. and Taha, H., (1999) Characterizing the Fabric of the Urban Environment: A Case Study Of Sacramento, California, Lawrence Berkeley National Laboratory, US Department of Energy. LBNL-44688.

Arnfield AJ (2003) Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water, and the Urban Heat Island. International Journal of Climatology 23:1–26

Asaeda T., Ca V.T., Wake A. (1993) Exchange Processes at the Land Surface for a Range of Space and Time Scales (Proceedings of (he Yokohama Symposium, July 1993). IAHS Publ. no. 212.

Asaeda T., Ca V.T., Wake A. (1996) Heat Storage of Pavement and Its Effect on the Lower Atmosphere. Atmospheric Environment Vol.30, No.3: pp. 413-427.

Bryan, Harvey Ph.D., FAIA. (2001) “Outdoor Design Criteria for the Central Phoenix/East Valley Light Rail Transit System” Cooling Frontiers: The Advanced Edge of Cooling Research and Applications in the Built Environment, Herberger Center for Design Excellence, pp 5.1-5.7

Bruse, Michael, ENVI-met website (n.d.) retrieved on January 16, 2008 from: http://www.envimet.com/

Celestian, S. B., and C. A. Martin. (2004) Rhizosphere, Surface, and Under Tree Canopy Air Temperature Patterns at Parking Lots in Phoenix, AZ. Journal of Arboriculture 30:245-252.

Chalfoun, N.V. et al, (1991) "MRT" Update: A Study on the Thermal Effect of Dry and Wet Paving and Landscape Materials on Restoring Human Thermal Comfort Conditions at Outdoor Spaces. The International Solar Energy Society (ISES) Solar World Congress Conf. August 17-24, 1991, Denver, Colorado.

Doll D., Ching J.K.S., Kaneshiro J. (1985) Parameterization of Subsurface Heating for Soil and Concrete Using Net Radiation Data. Boundary• Layer Meteorol. 32: 351-372.

Emmanuel R, Fernando HJS, (2007) Urban Heat Islands in Humid and Arid Climates: Role of Urban Form and Thermal Properties in Colombo, Sri Lanka and Phoenix, USA, Climate Research, Volume 34, Issue 3, September 2007, pages 241-251.

Golden, J.S., (2003) The Built Environment Induced Urban Heat Island Effect in Rapidly Urbanizing Arid Regions—A Sustainable Urban Engineering Complexity. Environ. Sci. J. Integr. Environ. Res., 2004, 1(4), 321–349, 2003–2004.

Golden, J.S. and Kaloush, K. (2006) Meso-Scale and Micro-Scale Evaluations of Surface Pavement Impacts to the Urban Heat Island Effects. The International Journal of Pavement Engineering. 7(1): 37-52. March 2006.

Golden, J. and Kaloush, K. (2007) Alternative Pavements Ease Urban-Heat Effect, retrieved on October 12, 2009 from: http://sos.asu.edu/news/greentalk/alternative-pavements-ease-urban-heat-effect

Lahme, E.; Bruse, M. (2003) Microclimatic Effects of a Small Urban Park in Densely Built-up Areas: Measurements and Model Simulations ICUC5, Lodz 1-5- September 2003

Nakamura, Y., Oke T. (1988) Wind, Temperature and Stability Conditions in an East-West Oriented Urban Canyon. Atmospheric Environment 22: 2691-2700.

Nunez M., Oke, T. R. (1977) The Energy Balance of an Urban Canyon. J. Appl. Meteorol.16: 11-19.

Olgyay, V. , (1963) Design with Climate: A Bioclimatic Approach to Architectural Regionalism, Princeton University Press, Princeton.

Oke T. (1981) Canyon Geometry and the Nocturnal Urban Heat Island: Comparison of Scale Model and Field Observation. International Journal of Climatology, 1: 237-254.

Oke T.R. (1987) Boundary Layer Climates. Methuen. London.

Pomerantz, M., B. Pon, H. Akbari, and S.-C. Chang. (2000) The Effect of Pavements' Temperatures on Air Temperatures in Large Cities. Paper LBNL-43442. Lawrence Berkeley National Laboratory, Berkeley, CA. See also Cambridge Systematics. 2005. Cool Pavement Draft Report. Prepared for U.S. EPA.

Taha, H., Sailor, D., & Akbari, H. (1992) High-albedo materials for reducing building cooling energy use. Berkeley, CA: Lawrence Berkeley National Laboratory Report No. 312721 UC-350: 71.

Taha, H. (1997) Modeling the Impacts of Increased Urban Vegetation on the Ozone Air Quality in the South Coast Air Basin. Atmospheric Environment, 30, 3423–3430.

Toudert, Fazia Ali, (2005) Dependence of Outdoor Thermal Comfort on Street Design in Hot and Dry Climate, Freiburg : Meteorologisches Instituts der Albert-Ludwigs-Universität, 2005.