J12.2 PHOENIX URBAN HEAT ISLAND EXPERIMENT: MICROMETEOROLOGICAL ASPECTS

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1. INTRODUCTION

There is growing concern in recent years about the increase in night time temperatures in Phoenix, especially after experiencing a 35.6 °C minimum on July 17, 2003. Minimum temperatures failing to fall below 38 °C may be possible in the near future as the magnitude of the Urban Heat Island (UHI) increases along with the rise in global temperatures. From 1960 to 2000, Phoenix experienced a minimum temperature rise of 0.47 °C per decade, which is one of the highest rates in the world for a city of this size (Golden, 2004). Much of this rise in temperatures is due to the increase in built-up areas and impervious surfaces, increasing the magnitude of the UHI throughout the city. In order to make general statements of the UHI phenomenon in Phoenix and other cities in hot arid climates, there needs to be a better understanding of the micro-local scale complexities within the urban fabric.

A one day field campaign was conducted in April 2008 to collect surface and ambient temperatures within various landscapes in Central Phoenix, Arizona. The goal of the field campaign was to create a detailed record of temperatures over a complete diurnal period, which could then be used to compare with modeling and to better understand the causal factors of the UHI within the built environment.

The three-dimensional microclimate numerical model ENVI-met was then used to simulate temperatures and the UHI at three distinct locations over the same diurnal period as the field data collection. ENVI-met model inputs were further refined and made more accurate by the use of free tools available on the internet, as well as by identification of individual trees, vegetation, and building materials in the field.

When compared with field measurements, model simulations were able to replicate the highest UHI in the downtown area a few hours after sunset, but under-predicted the high and low temperatures at each study site during the 24-hour period.

2. BACKGROUND

Within the urban canopy layer, building geometry and surface thermal properties have been shown to have the largest effect on the magnitude of the UHI (Oke, 1982, 1987). Measurement of building geometry includes 1) building height/canyon width (H/W) ratio, 2) sky view factor, which is the proportion of sky seen from an outdoor point in space (Grimmond *et al*., 2001), and 3) a compactness index, which is the ratio of building surface area to the surface area of a cube which has the same volume as the building (Unger, 2004; Emmanuel and Fernando, 2007). Other causal factors of the UHI include anthropogenic heat release from buildings and vehicles on the roadways, loss of evapotranspiration due to reduced vegetation and latent heat transfer, and the loss of wind within the built environment to transport heat out of the city (Oke, 1988).

Cities in hot dry climates, because of the typically stable conditions with clear skies and light winds, often have high UHI magnitudes, even when measured in smaller cities of 30,000 people (Hedquist, 2005), or measured at the microscale within a metropolitan area (Hawkins *et al*., 2004). Previous research in Phoenix has shown that the UHI magnitude can be as much as 10-11 °C three to five hours after sunset (Hedquist and Brazel, 2006; Fast *et al*., 2005).

While infrared thermography has been done from both ground and airborne-based platforms in previous studies (Voogt and Oke, 1997; Ben-Dor and Saaroni, 1997), the use of hand-held infrared thermography for microscale UHI studies is a more recent technique. This is most likely due to recent improvement in resolution and portability of thermal infrared cameras, such as the hi-definition FLIR ThermaCAM SC640 (FLIR, 2008).

In Phoenix, hand-held infrared thermography was used recently to study the thermal properties of surfaces, principally pavements, at Sky Harbor International Airport (Carlson, 2005). Carlson used the FLIR ThermaCAM S60 camera to measure diurnal temperature patterns throughout the airport property, using GIS software to compare surface properties to image temperatures. Thermal images, when compared to land cover type percentages derived from GIS shape files, identified the most significant contributing factors to highest microscale temperatures at the airport.

The microclimate numerical model ENVI-met stands for “Environmental Meteorology” and was created by Michael Bruse as part of a PhD thesis in Germany (Bruse, 1998). It is especially advantageous for research conducted at a fine scale resolution, with typical grid cell resolutions between 0.5 and 10 m in space, and 10 sec in time. Several variables can be simulated, including flow around and between buildings, exchange processes of heat and vapor at the ground surface and at the walls, turbulence, exchange of vegetation and vegetation parameters, bioclimatology, and particle dispersion (ENVI-met, 2008).

In order to run the model, the user must have detailed soils, buildings, vegetation, and initial atmospheric conditions for the model domain of interest. The file used to input spatial information has a user-friendly graphical interface. However, correct use and

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set up of the model for a specific area requires a thorough background in meteorology and a good knowledge of the study area domain to be simulated. Principal initial atmospheric conditions needed to run simulations for specific model domains include the following:

- Wind speed and direction at 10 m above the ground
- Roughness length (Z_o)
- Initial temperature of the atmosphere
- Specific humidity at 2500 m
- Relative humidity at 2 m

In hot and dry climates, ENVI-met has been tested recently in Ghardaia, Algeria and Phoenix, Arizona (Ali-Toudert and Mayer, 2006; Emmanuel and Fernando, 2007). With the use of ENVI-met simulations to test various urban canyon aspect ratios and orientation effects on outdoor thermal comfort, Ali-Toudert and Mayer (2006) were able to confirm the strong correlation between canyon ratios and orientations and the amount of human comfort within these canyons.

3. METHODS

3.1 *Field Data Collection*

In order to create a baseline of temperature measurements for comparisons with ENVI-met simulation results, field data were collected during a 24 hour period beginning at 0600 LST 4 Apr 2008. The date chosen had relatively clear skies, calm winds, and lower humidity. Multiple field measurement techniques were utilized to collect both surface and ambient temperature diurnally. Field measurements of temperature were both on the ground at a fixed location (downtown Phoenix), with mobile sampling, and via helicopter. Figure 1 illustrates the study area and data collection route across mixed land uses in Phoenix, the locations of modeling domains, and the two weather stations used for model input.

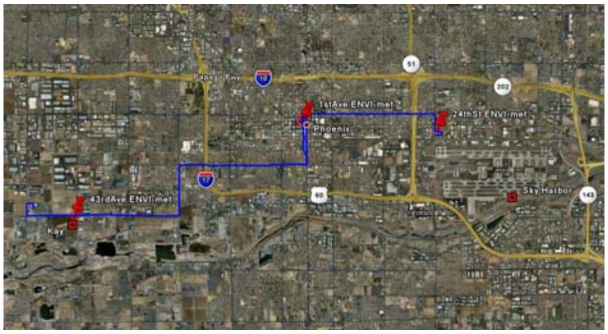

Figure 1. Study area, with mobile and helicopter route indicated by blue line and red pushpins indicating microclimate simulation domain areas. In situ weather stations used in the study are indicated by red squares.

Mobile sampling by vehicle of surface and ambient temperature, as well as relative humidity occurred approximately every two hours beginning at 0600 LST 4 Apr 2008 and ending at 2300 LST 4 Apr 2008 (ending earlier than 24 hours due to power supply issues). A total of 13 one-hour long mobile samples were conducted by two separate vehicles traveling in opposite direction along an east-west route across central Phoenix.

Equipment mounted on the vehicles consisted of a temperature and humidity sensor, an infrared surface temperature sensor, and a GPS to record location. Measurements were recorded every second with a consistent average vehicle speed of 50-60 km/hr, giving a reading of temperature approximately every 7-8 m along the route. The route itself was 16 km in length from east to west. Information obtained while the vehicle was not moving, whether from traffic congestion and/or traffic lights, was eliminated from the record after data collection was completed. Equipment used in mobile sampling of the UHI through Central Phoenix included two of each of the following:

- Campbell Scientific CR10X Datalogger
- IRTS-P Apogee Precision Infrared Thermocouple Sensor
- Vaisala HMP45C Temperature and RH Probe
- GPS16-HVS Garmin GPS Receiver (WAAS-enabled, 12 channel)
- Campbell Scientific UT12VA 12-Plate Gill Radiation Shield
- Laptop computer, used to monitor and download sensor data
- Other equipment, including cables, mounting equipment, and power adapter

Figure 2 illustrates the completed set-up mounted on a vehicle.

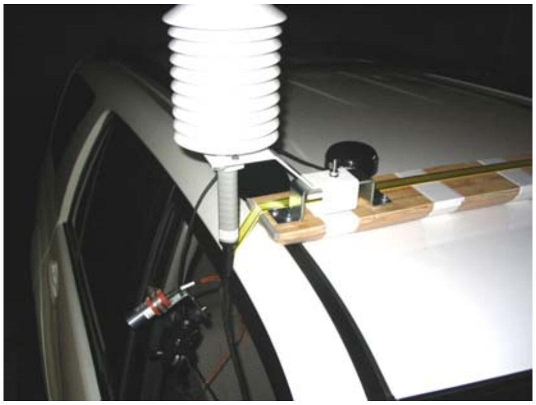

Figure 2. Mobile sampling equipment, with GPS, ambient temperature sensor, and IR thermometer shown mounted on top and side of vehicle.

IR thermal images of surface temperature were captured with a FLIR ThermaCAM S60 at key locations within the Downtown Phoenix ENVI-met modeling study area. Images of street canyons and building façades were acquired over the space of an hour, every two hours during the 24 hour field day. Acquisition times correspond to mobile sampling measurements, beginning at 0600 4 Apr 2008 and ending at 0700 5 Apr 2008. Careful consideration was taken by the field crew at this location to attempt to acquire imagery down the N/S 1st Avenue street canyon at approximately the same time as the mobile vehicle and helicopter were traveling through the canyon.

An innovative method was used for transportation between image acquisition sites with the use of a "pedal cab," a type of bicycle taxi. The downtown field crew was able to acquire a much greater number of thermal images with this type of transportation within the street canyons than would have been possible with a vehicle or by walking between sites. A much more detailed description of this portion of data collection, methods, and results can be found in a companion conference paper (Di Sabatino *et al*., 2009).

IR thermal and visual images were captured via a high-resolution FLIR SC640 camera from a Phoenix KPNX Channel 12 News helicopter at approximately 300 m above the ground, and along the mobile route path from east to west at three separate times of the day on 4 Apr 2008. It was decided that 1400, 1900, and 2200 LST were the best times to follow the mobile vehicle and route and acquire imagery during the field campaign. Capturing imagery from the helicopter allowed for high definition surface radiant temperature measurements to be made across central Phoenix, at a much larger scale than would be possible by the downtown ground team alone.

The thermal infrared camera was held, at 45 ^{o}, out the left passenger side of the helicopter. Previous research has shown that this angle, as well as nadir (90 ^{o}), are optimal for detecting differences in the ground, wall, and roof temperatures (Voogt and Oke, 2003). Since it was not possible to mount the camera to the bottom of the helicopter for nadir measurements (due to FAA regulations and time constraints to obtain permission to do so), the camera was pointed toward the ground at the 45 ^{o} angle throughout the duration of each one hour flight. The camera captured both visible and infrared images simultaneously along the mobile transverse route, with several images captured per minute in flight.

Preliminary testing of thermal images captured by the FLIR SC640 illustrated the dramatically improved difference of high definition over lower resolution cameras used in previous studies capturing thermal images from the air, such as images captured in a Chicago UHI study (personal communication with J. Carlson, 2008). The SC640 has a resolution of 640X480 pixels versus 320x240 pixels for the FLIR ThermaCAM S60 used by the ground thermography team in downtown Phoenix (FLIR, 2008). The high resolution of images from the helicopter allowed for a greater ability to detect microscale differences in radiative temperatures from various ground surfaces, especially valuable for comparing with mobile, ground (downtown) and simulated temperatures during the April field study day.

3.2 *ENVI-met Testing and Refinement for Phoenix*

Each microclimate simulation area required two files for initialization: a configuration file (.cf) and an area input file (.in). The area input files were created for each domain based on aerial imagery from Google Earth, building height obtained from the internet, Los Alamos Labs, and from still images taken from the FLIR SC640 camera via helicopter during the 1400 acquisition time. Configuration files, consisting of initial atmosphere conditions near the ground & top of the atmosphere, as well as building and soil material (temperature & humidity), where obtained from two weather stations: Sky Harbor ASOS (for 24th St & 1st Ave), and Kay PRISMS (for 43rd Ave). Soil temperature & relative humidity values were obtained from a representative urban station, Mesa AZMET (downloaded at http://ag.arizona.edu/azmet/).

Since ENVI-met was designed in Germany for a European city, default input parameters, such as trees, vegetation, and building materials are not accurate for the urbanized arid climate of Phoenix, Arizona. Therefore, identification of specific building materials and vegetation native to the area within each model domain was undertaken to increase the accuracy of model output. Identification of specific trees and other vegetation was made possible with the aid of free online tools such as 'street view' in Google Earth, field observations, and from the expertise of an arborist who works for the city of Phoenix. Trees planted along streets in Phoenix, suited for a hot, arid climate, were generally found to have heights of 5-10 m and had lower density canopies than those found in the default settings available in ENVI-met. Figure 3 illustrates the model area input file for the downtown 1st Ave site, with buildings indicated by grey and green colors representing trees, shrubs, or grasses.

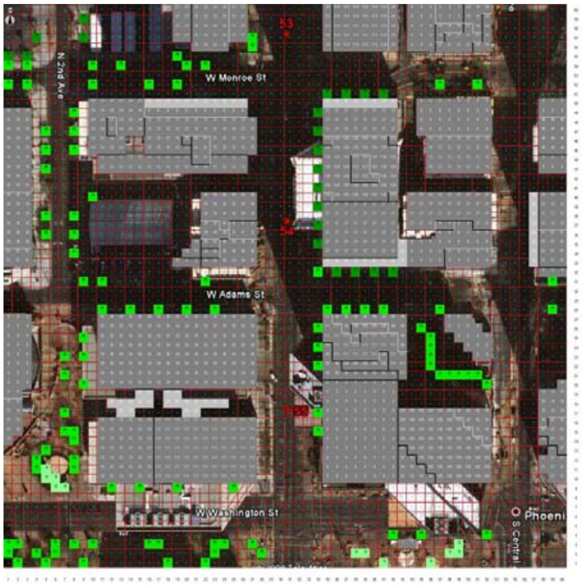

Figure 3. Final ENVI-met area input file for the 1st Ave study domain.

3.3 *Land Cover Comparisons*

After refining the ENVI-met 5 m grid inputs, an accurate land cover classification was created for each of the three domains. Spatial databases were created to define individual characteristics of each grid cell, including building material type and height, vegetation height and type, as well as impervious surface types. Each of the three study domains has a unique breakdown of building density, impervious surfaces, and amount of vegetation. It is clear that the 1st Ave site has the largest percentage of impervious surfaces, such as concrete and asphalt, while the 43rd Ave site, predominantly consisting of agriculture, has the largest percentage of pervious soils. 1st Ave also has the highest density and percentage of buildings occupying grid cells at 34%, followed by the much less dense area of 24th St at 8% coverage. Figure 4 illustrates the land cover characteristics for each of the three modeling domains.

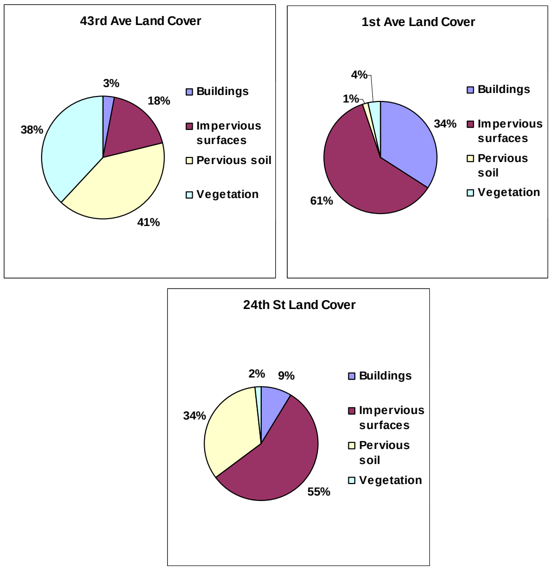

Figure 4. Land cover classifications of model domains in Central Phoenix.

4. RESULTS

4.1 *Model Output*

Simulation outputs for ambient temperature throughout the 24 hour period generally under-predicted the maximum observed temperature and over-predicted the minimum temperature. This smaller diurnal temperature range prediction is similar to the results found in Emmanuel and Fernando (2007). However, at the time of maximum UHI magnitude (2200), the model simulations were the most accurate, especially for the downtown 1st Ave area. Figure 5 illustrates the model output at 2200 within the 1st Ave domain, overlaid in Google Earth 3D. The temperature scale, shown in the lower right of the figure, ranges from 22.7-23.2 °C, with the highest reading in the northwest and lowest readings underneath higher density ficus trees in the southeast quadrant of the domain. Figure 6 illustrates the simulation output for the 24th St area for comparison purposes. Temperatures were generally 1 °C lower for this area, which is due to the lower density of buildings and higher percentage of pervious surfaces, allowing for higher rates of cooling after sunset. Output for the 43rd Ave area is not shown, but average temperatures for the domain for the 2200 time are similar to the 24th St area.

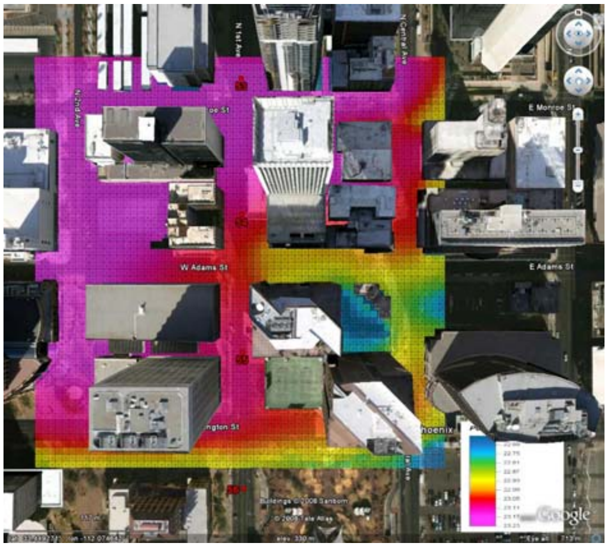

Figure 5. ENVI-met output for ambient temperatures at 2200 for the 1st Ave domain. Temperatures displayed are at 1.5 m. Numbers 53-56 correspond to 10 m increments of mobile measurements.

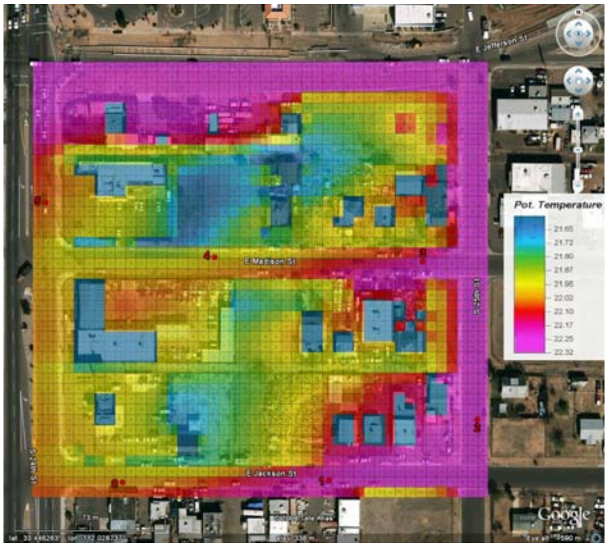

Figure 6. ENVI-met output for ambient temperatures at 2200 for the 24th St domain. Temperatures are at 1.4 m. Numbers 0-5 correspond to 10 m increments of mobile measurements.

4.2 *Model Validation*

ENVI-met simulations from the April 2008 field day were statistically compared with mobile sampling observations within the three domains at the 1400, 1900, and 2200 times. This was done in order to be able to make further comparisons with helicopter thermography, which was acquired at the same respective times. Root mean square error (RMSE) values indicate that the 2200 model simulation times most closely matched the mobile observations out of the 1400, 1900, and 2200 times. The model generally under-predicted the afternoon maximum temperatures and over-predicted the nighttime minimum temperatures for all three study domains.

RMSE values for point locations in the simulation domains corresponding to mobile measurements ranged from 1.10 at 2200 to 2.11 during the 1900 time. Index of agreement values were very strong, with values of 1 for all three times. While most of the error was systematic, strong index of agreement and high R^2 values indicated that the model performed well when compared to mobile observations along roadways.

4.3 Thermography comparisons

Preliminary comparisons between helicopter thermography and mobile observations of surface temperatures along roadways indicated a close agreement of temperature values at specific point locations. During the three times of helicopter image acquisition, surface temperatures along roadways varied by only 0.1-0.5 ^{o}C at specific points between mobile and helicopter values.

Model simulations had much higher errors when calculating the surface radiant temperatures, with over-predicted values that were as much as 25-30 ^{o}C higher than helicopter and mobile measurements during the 1400 afternoon time. However, for the 1st Ave downtown site, simulations at 2200 of surface temperatures were within 5 ^{o}C of mobile and helicopter measurements.

5. CONCLUSIONS

This field experiment, with data collected over a complete diurnal period in Central Phoenix has been invaluable in gaining a better understanding of the UHI at the micro-local scale within a large, arid city. While the sample period is only from one day and a snapshot in time, the spatial and temporal resolution of both data collected and model simulations allows for a much more comprehensive and rigorous analysis of the heat island and the effects of the built environment, which would not be possible from in situ weather stations alone.

The use of ENVI-met for microscale study of the UHI shows promise as a freely-available tool off the internet, especially with the next version (4.0) coming out soon which promises higher accuracy of building heat transmission parameters. After increasing the accuracy of the model inputs for a hot, arid city, simulations of ambient temperature were most accurate at the time of maximum heat island intensity, 3-5 hours after sunset. In the daytime, the model was also able to accurately simulate the effect of building height and shading on surface temperatures. Methods used in this paper to refine model input using field observations and free tools off the internet can be applied to other urbanized areas to study the effects of the built environment on temperatures and the UHI.

Work in progress includes a comparison of model simulations results between default input settings (no change to vegetation and building heat transmission and albedo values) and refined input settings for Phoenix, containing actual arid trees and estimated heat and albedo values for specific building materials. Simulations are also being run for select days of the year to compare seasonal effects of the built environment on temperature within the three model domains discussed in this study, including a summer day in 2008 with a very uncomfortable minimum temperature of 32.2 ^{o}C.

6. ACKNOWLEDGEMENTS

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