RESULTS FROM THE PHOENIX ARIZONA URBAN HEAT ISLAND EXPERIMENT

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Abstract

A 24 hour Urban Heat Island (UHI) field experiment was conducted in Phoenix, Arizona on April 4-5, 2008. IR thermography was utilized to measure temperatures over a large area ranging from meter to km scales, augmented by standard meteorological measurements. Temperature mapping was achieved utilizing field measurements at fixed locations on the ground, with mobile sampling, and via helicopter. Analyses of measurements illustrate the effects that various building façade material and building arrangements have on diurnal air temperatures. The numerical model ENVI-met as well as CFD modeling of the CBD, were used to interpret local flow modifications due to the UHI diurnal cycle. Results are of relevance for devising heat mitigation strategies within large hot and arid cities and developing urban parameterizations for meso-scale models.

Key words: Urban heat island, Thermography, ENVI-met, CFD modeling

1. INTRODUCTION

Motivated by the concerns of recent increase in night-time air temperatures that afflict the Phoenix Metropolitan Area, an intensive 24 hour field campaign was conducted in April 2008 to collect surface and ambient temperatures within various landscapes in Central Phoenix, Arizona, including a four-block area of the Central Business District (CBD). The goal of the field campaign was to create a detailed record of both surface and ambient temperatures within the urban canopy over a complete diurnal period, which could then be used to compare with numerical modeling outputs to gain a better understanding of the causes of the Urban Heat Island effect (UHI) within the built environment of Central Phoenix, Arizona.

The effect of buildings on flow and temperature fields within the urban canopy layer has been studied recently, with several urban flow and energy parameterizations available. However, there are few studies addressing the thermal aspects of the urban environment and the spatial temperature distribution within urban street canyons. In a recent paper by Solazzo and Britter (2007) it has been outlined that in most real scenarios buoyancy effects are confined to near the wall and therefore a little contribution to the overall flow structure is to be expected. Yet, Di Sabatino *et al.* (2009) showed that there is an appreciable effect of surface temperatures on the flow fields

Previous research in Phoenix has shown that the UHI magnitude can be as much as 11^{o}C (Hedquist and Brazel, 2006; Hedquist *et al.*, 2009). An overall increase in night-time and minimum temperatures in the built environment of Phoenix in recent years has prompted policies to mitigate heat within the city. A recent study done by Emmanuel and Fernando (2007) tested various heat mitigation scenarios using ENVI-met in the CBD of Phoenix. The authors found that an increase of building density leads to more shading during the day and cooler temperatures, thus leading to lower radiant temperatures and an increase in outdoor thermal comfort. .

The three-dimensional microclimate numerical model ENVI-met was used to simulate temperatures at three distinct locations within Central Phoenix over the same diurnal period as the field experiment. ENVI-met model inputs were further refined and made more accurate by the use of free web-based tools, as well as by identifying individual trees, vegetation, and building materials in the field. In the downtown area, an analysis was made between IR thermal images of building facades and their respective materials. CFD modeling was then implemented along the 1st Ave street canyon to evaluate modification to the flow due to façade differential heating during the time of the field experiment, in relation to building density, height, and orientation along the street canyon.

2. EXPERIMENTAL DESCRIPTION

2.1. 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 06:00 LST 4 Apr 2008. This day had relatively clear sky, calm winds, and low relative humidity. 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.

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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 temperature sampling by vehicle occurred approximately every two hours from 06:00 LST 4 Apr 2008 to 23:00 LST 4 Apr 2008 (ending earlier than 24 hours due to power supply issues). Equipment mounted on the vehicles consisted of a temperature and humidity sensor, an IR 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 was 16 km in length from east to west. Greater details of the mobile equipment, including a picture of the equipment can be found in Hedquist *et al*. (2009). IR thermal and visual images from the air were captured by the high definition FLIR SC640 camera using 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 14:00, 19:00, and 22:00 LST 4 Apr 2008.

IR thermal images on the ground were captured with a FLIR ThermaCAM S60 at key locations within the CBD. Images of street canyons and building façades were acquired once, every two hours, for a total of 13 times during the 24 hour field day. Acquisition times correspond to mobile sampling measurements, beginning at 06:00 4 Apr 2008 and ending at 07:00 5 Apr 2008. Quick acquisition of images was made possible by transportation via a "pedal cab," a type of bicycle taxi. A much more detailed description of data collection, methods, and results in the CBD of Phoenix, can be found in Di Sabatino *et al*. (2009).

2.2. ENVI-met Simulations

ENVI-met simulation domains, located at 24th St (near Sky Harbor Airport), 1st Ave (downtown), and 43rd Ave (open, agricultural fields), were tested and refined for an arid region. This was accomplished by identifying specific building materials and vegetation native to the area with the aid of free online tools such as 'Street View' in Google Earth, field observations, and from the expertise of the principal arborist 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. Simulations were run at the three domains for a 24 hour period beginning at 10:00 LST 4 Apr 2008 using Sky Harbor Airport (24th St and 1st Ave) and Kay PRISMS (43rd Ave) weather stations for initial atmospheric conditions.

2.3. Downtown Thermography & CFD modeling

A general numerical Computational Fluid Dynamics (CFD) model was employed to aid IR thermography and ambient temperature measurement interpretation in the CBD of Phoenix. In particular, we were interested in possible flow modifications induced by temperature surface gradients which were not directly measured during the experiment as well as identifying temperature distribution within the street canyons. As we were mainly interested in flow modifications occurring at the street canyon and building scale, a single street canyon was chosen for detailed numerical investigations. In particular, we chose the 1st Ave street canyon, as temperature measurements were available for almost all buildings forming the canyon. A similar choice was made by Hedquist *et al*. (2009) in their numerical simulations using ENVI-met. Details of the CFD modeling set-up and equations used can be found in Di Sabatino *et al*. (2009). Figure 2 shows the street canyon geometry used in the CFD simulations. Building shapes are partially simplified with respect to the real ones, but we maintained the same building heights and relative distances between buildings as reality. Overall, the street canyon is asymmetric as buildings at both sides do not have the same height. The heights of buildings range from 10 m to 120 m, while the street canyon width W is equal to 49 m. The "average" height of buildings at both sides is about 60 m leading to an aspect ratio H/W equal to about 1.2. However, it is clear that the flow which developed inside the canyon was strongly affected by the large building height variability. Moreover, an intersection is also present in the geometry affecting the flow substantially. Simulations over the entire CBD study area were also performed in neutral atmospheric conditions for some wind directions to investigate the overall in-canopy flow pattern over the study area. For these simulations the total area enclosed by the buildings is 128 m by 254 m.

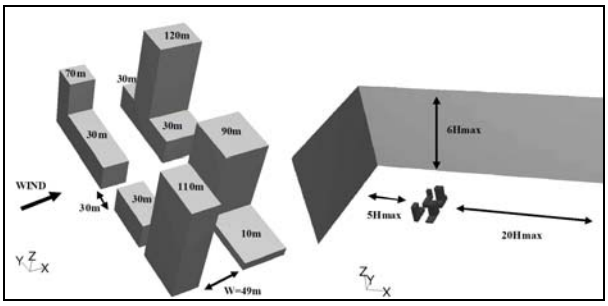


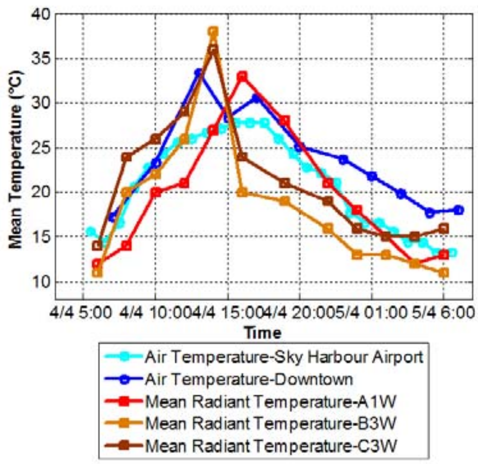
Figure 2. Sketch of the street canyon geometry (left graph) with the height of each building indicated on the roof and details of the computational domain (right graph) used for street canyon CFD simulations.

3. RESULTS

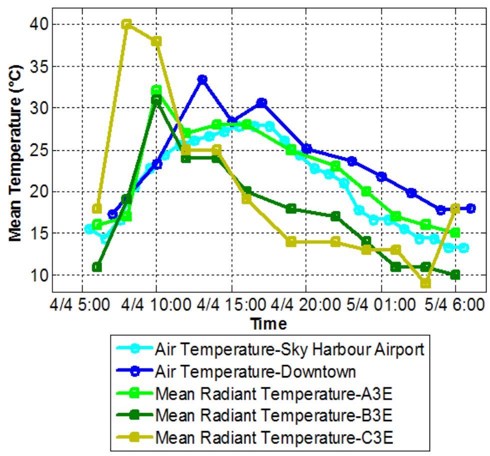
3.1. Micro-Local Scale Temperature Analyses

Analysis of IR thermography of building facades in the downtown revealed a sharp contrast in temperature differences depending on the time of day, height and orientation of the building and surrounding buildings, as well as wall material itself. The highest temperatures at 22:00 tended to occur on south and west facing façades, containing brick or dense concrete. Glass and metal facades tended to warm and cool more rapidly, which one would expect from previous findings and literature.

Along the mobile/helicopter route, the highest temperatures at 14:00 tended to be along roadways close to the 24th Street domain, with low building density, high amounts of impervious surfaces, and mainly devoid of vegetation and shading. The highest temperatures at 22:00 were within and just to the south of the 1st Ave street canyon, where there was heat trapped within canyon walls, as well as large amounts of heat released from pavements and building walls from prior radiative heating. Based on the analysis of IR images, Figure 3 summarizes the main features of warming/cooling diurnal cycle experienced by the façades in the Phoenix CBD.



a)



b)

Figure 3: Mean radiant temperatures measured at a) western and b) eastern building façades. Profiles of air temperature downtown and at Sky Harbor Airport are also reported.

The figure shows the diurnal variation of the mean radiant temperature from the façade of six buildings taken as representative of the three N/S street canyons denominated A (1st Ave), B (Central) and C (1st St) together with air temperature measured downtown and at Sky Harbor Airport. Figure 3a) shows results from building façades facing West and Figure 3b) shows those from the opposite side of the canyons. Overall air temperature behavior downtown followed that of the building façade temperature with a peak a few hours after that on the West side façades. A close inspection of IR data reveals that the mean radiant temperature as shown by Di Sabatino *et al.* (2009) is the result of an average of very different temperature values. All buildings show a very heterogeneous temperature distribution due to a combination of different surface albedo, material thermal inertia and shadowing effects. It was observed that canyons A, B and C show a warmer layer near the ground. This can be interpreted as discussed in Di Sabatino *et al.* (2009) in terms of flow separations determined by double vortexes structure within each street canyon. This effect is still under consideration and can be confirmed by detailed CFD simulations.

3.2. ENVI-met & CFD Simulations

ENVI-met simulations run for the 24 hour field study period reasonably well replicated the influence of building density, surfaces, and vegetation on the diurnal temperature pattern and UHI. During the mid-day time period of maximum temperatures, the downtown area experienced the coolest temperatures, especially within street canyons with the highest amount of shade from tall buildings, with the highest temperatures within the domain close to Sky Harbor Airport, with lower building density and high amounts of impervious surfaces. In the early evening, the downtown domain had the warmest temperature, with heat being released from the built environment, while the coolest area was at the 43rd Ave site, with open, agriculture fields and high amounts of vegetation. Figure 4 illustrates the potential temperature patterns in the afternoon and evening for the 1st Ave domain. The evening simulation shows how ambient temperature can vary up to 1˚C within 10-20 m.

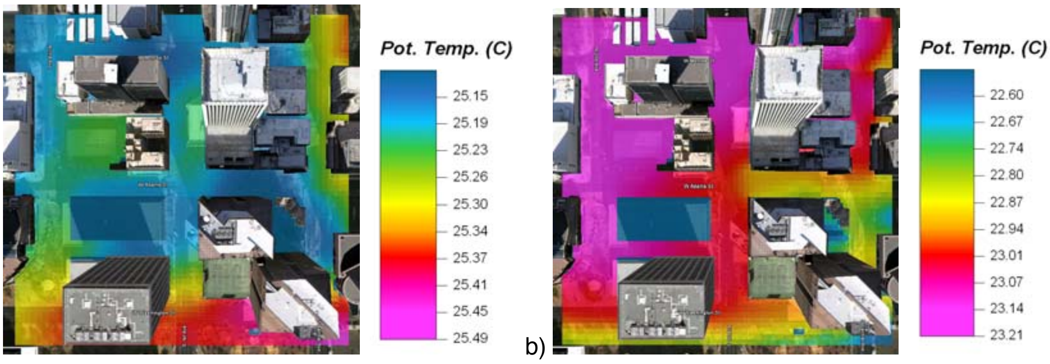


Figure 4. Simulations of potential temperature (1.5 m) at the 1st Ave domain for a) 14:00 and b) 22:00.

Detailed CFD simulations for 1st Ave showed that differential heating imposed as boundary condition for all street canyon building façade alter the flow structure which however remains separated into two main regions. The lowest one has a scale of about W and is characterized by minimal air entrainment from the top. This partially justifies the lowest region being warmer through the night.

4. DISCUSSION & 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 micro-scale study of the UHI shows promise as a freeware numerical modeling tool. 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, creating a small 'cool island' in the CBD with higher building density (Pearlmutter *et al.* 1999). Results from this study can aid in understanding the dynamics of the UHI within the built environment as well as finding solutions to mitigate heat and increase outdoor thermal comfort in hot, arid cities.

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