Preliminary Test of a Surface Heat Island Model (SHIM) and Implications for a Desert Urban Environment, Phoenix, Arizona

ANTHONY J. BRAZEL, Department of Geography, Arizona State University, PO Box 870104, Tempe AZ 85287-0104 (Correspondence address: Center for Environmental Studies, Arizona State University, PO Box 873211, Tempe AZ 85287-3211); and
KATHERINE CREWE, School of Planning and Landscape Architecture, Arizona State University, PO Box 872005, Tempe AZ 85287-2005

ABSTRACT

Rapidly expanding desert populations have significantly altered surface microclimatic conditions. These modifications are evident for much of the year, since desert areas are frequently affected by stable, clear, calm weather. Past empirical analyses of urban effects for Phoenix and Tucson, Arizona, have highlighted the large magnitude of the "urban heat island effect" with minimum temperatures in summer changing by over 5°C from the 1940s to present. Less understood are links of the built environment to surface microclimate within the urban area. This paper presents field data taken for a short sample period in summer in Tempe, Arizona, from an "urban canyon" environment, an asphalt lot, and a nearby irrigated park. A Surface Heat Island Model (SHIM) compares favorably with these field data. The model is a "force-restore" scheme to estimate post-sundown surface cooling at night – the time of most evident development of urban heat islands. The model incorporates thermal, morphological, and geometric features of the urban area that promote considerable change of local microclimates. A sensitivity analysis of key variables yields insights into challenges to ameliorate heat islands. Key are use of low thermal admittance materials, considerations of building height/width ratios, sky view factors, and judicious use of evaporative surface water cooling. For urban ecological studies, the use of modeling together with neighborhood scale monitoring is encouraged to assist in unraveling the intra-urban variance of microclimates and effects on ecosystem processes.

INTRODUCTION

The majority of desert cities are located in regions of frequently stable, clear, calm weather and typically experience wide ranges in diurnal thermal conditions (e.g., Golany 1988, Pearlmutter and Berliner 1998). Under this kind of climate regime, local effects of the earth's surface and terrain are accentuated. As a result of rapid urban growth in many desert cities, year-to-year temperature trends of urban weather stations are impacted by local land-use and land-cover variations (e.g., Brazel et al. 2000, Comrie 2000). Hansen et al. (1999), for example, use the Phoenix, Arizona, station to illustrate the dramatic effects of an urban-dominated data point even in interpolation of regional gridded temperatures for global assessment (an interpolation in which one "odd" urban data point affects representation of the mapped temperatures over distances 1,000 km around the data point). They have devised an empirical method to de-trend these data for urban effects (Hansen et al. 1999). This is clearly necessary, since the temperature trend for Phoenix, as an example, shows a ca. 5.5°C increase in the minimum temperatures from the late 1940s to present, a large majority of which is due to urbanization (Balling and Brazel 1987, Brazel et al. 2000). What is less clear for any given urban-dominated weather site are the causes of these changes within the urban area at the neighborhood scale, and the links of urban ecosystems to changes in surface climate. Empirical temperature trends and analyses, per se, do not fully reveal causes of the urban effects. What is needed are models and integrated observational systems to monitor the urban environment.

In the last decade, urban climatologists have developed numerical models for investigation of cities and their climatic environments, and special efforts have been made to broaden the agenda for urban environmental studies. This is indicated by various symposia of the American Meteorological Society's Board on Urban Environments and the inception of two urban Long-Term Ecological Research (LTER) monitoring locations in the U.S – Phoenix and Baltimore (e.g., see Brazel et al. 2000). Urban ecologists, planners, climatologists, and other scientists would greatly benefit from making use of these models together with empirical field studies in urban ecological investigations. The models would assure more explanatory power for knowledge of urban ecological systems and to evaluate climate and planning scenarios for the future of desert cities.

The purpose of this paper is to present a set of field observations of typical June weather (June 2001) in Phoenix and to make use of the recently developed urban climate model to illustrate the controls of cooling from sundown to the near-minimum temperature time (SHIM - Surface Heat Island Model, reported in Voogt and Oke 2000). This phase of the diurnal cycle is critical to study, since it is known that local effects come into

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play after daytime regional convection processes subside near sundown, and when differential surface cooling ensues (e.g., Kirby and Sellers, 1987, Acevedo et al. 2001, Fernando et al. 2001). It is well known in urban climatology that the spatial variability of city temperatures maximizes after sundown to produce the heat island effect (Barton and Oke 2000). For example, for Phoenix it has been shown that daytime maximum temperatures demonstrate little trend over the last 50 years, whereas the minimum temperatures have increased dramatically and these temperatures display considerable spatial variability (Balling and Brazel 1987).

THE SHIM MODEL

The Surface Heat Island Model is available (in simple computer spreadsheet form) to simulate the cooling effects over variable urban/rural terrain as a function of the built features and rural aspects of any environment (e.g., materials and structure types, height/width of buildings, internal building temperatures, deep soil/material temperature, weather data). One form of the model can be accessed at: www.geog.ubc.ca/~pascal/research/ATSC/shim, but the authors also obtained an updated version from one of its originators, J. Voogt (Department of Geography, University of Western Ontario). The model acts as a mechanism to understand the highly complex nature of urban effects during nighttime (commencing at 6 pm), and is a "force/restore" model that calculates balances of the energy budget among the fluxes of longwave emitted and incoming longwave radiation at night (usually a net outward flux to space) and the subsurface heat flux, normally to the surface from depth at night. The model has been previously validated (Voogt and Oke 2000). A "rural" version of the model includes a turbulence term and expansion to consider the entire energy budget; the urban version as yet does not have this expanded analysis capability. Thus, the validity of the model, currently, is for low wind conditions – typical at any rate during maximum urban effect conditions.

The model requires estimates of several parameters for a given site. Critical ones are: (a) thermal admittance–energy $m^{-2}time^{-1}°K^{-1}$–a measure of heat storage character of the surface and subsurface, (b) estimate of longwave incoming radiation, (c) sky view factor (e.g., Grimmond et al 2001)–a "fish-eye lens" view of the sky, accounting for building obstructions (ranges from 1.0 for total unobstructed hemisphere to 0.0 for totally obstructed), (d) estimate of sundown temperature, (e) in the case of an urban canyon, the wall temperatures and internal building temperatures, and (f) an estimate of the 0.25 m (so-called deep) depth temperature in the material making up the surfaces and walls. Explanations of equations for the SHIM model can be obtained from perusing a Manual document stored at the above web site. Space limits extensive listing here. It should be noted that the model requires the 6 pm temperature to be known (this may be modeled with some other energy budget model).

THE FIELD OBSERVATIONS AND STUDY LOCATION

A field exercise was conducted for the period June 3-7, 2001 in Tempe, Arizona, primarily on the Arizona State University (ASU) campus, but also extending into the mesic residential community to the south of the campus (Fig. 1). From these data, comparisons of observations may be made with estimates of SHIM. Four field sites were established as part of an undergraduate geography field methods course during summer school at ASU, the purpose of which was to engage students in methods of sampling the urban environment and to introduce them to examples of typical field equipment used in climatology. Sites were established over an extensive asphalt parking lot (Lot 59 - N), between two campus buildings (UC - example of an "urban canyon"), over a smaller asphalt parking lot (S), and on the edge of an extensive flood-irrigated park to the south of campus in a predominantly mesic residential neighborhood (Daley Park - P). The class conducted two exercises: (a) a walking and mobile tour using field equipment (temperature and humidity sensors), walking through campus among fixed sites and driving the entire length from Lot 59 to Daley Park; and (b) establishing automated sensors at the four fixed points above (using HOBO Onset Corp automated data loggers recording temperature and dew point). Only the fixed-point data from sensors installed by the authors are analyzed in this paper and are used to compare to SHIM. Values from these sites were monitored on a 5-min interval during the sample period. All sensors were pre- and post-calibrated at the Office of Climatology at ASU. They were within <0.5°C of each other upon calibration check.

Figure 2a and b illustrate the diurnal 5-min temperatures and dew points at each site. The entire period of the sample consisted of clear skies. Generally, the period was quite typical of June in Phoenix with daytime values over 35°C and nighttime values in the 20s°C (Schmidli 1996). Dew points ranged from -7°C to over 5°C–again quite typical for the dry June period in Phoenix. Overall, the period showed a general warming from June 3-7.

Field results illustrate several common features of microclimatic variations within a city, for example: (a) shading at the urban canyon (UC) site during daytime, thus inducing cooling compared to

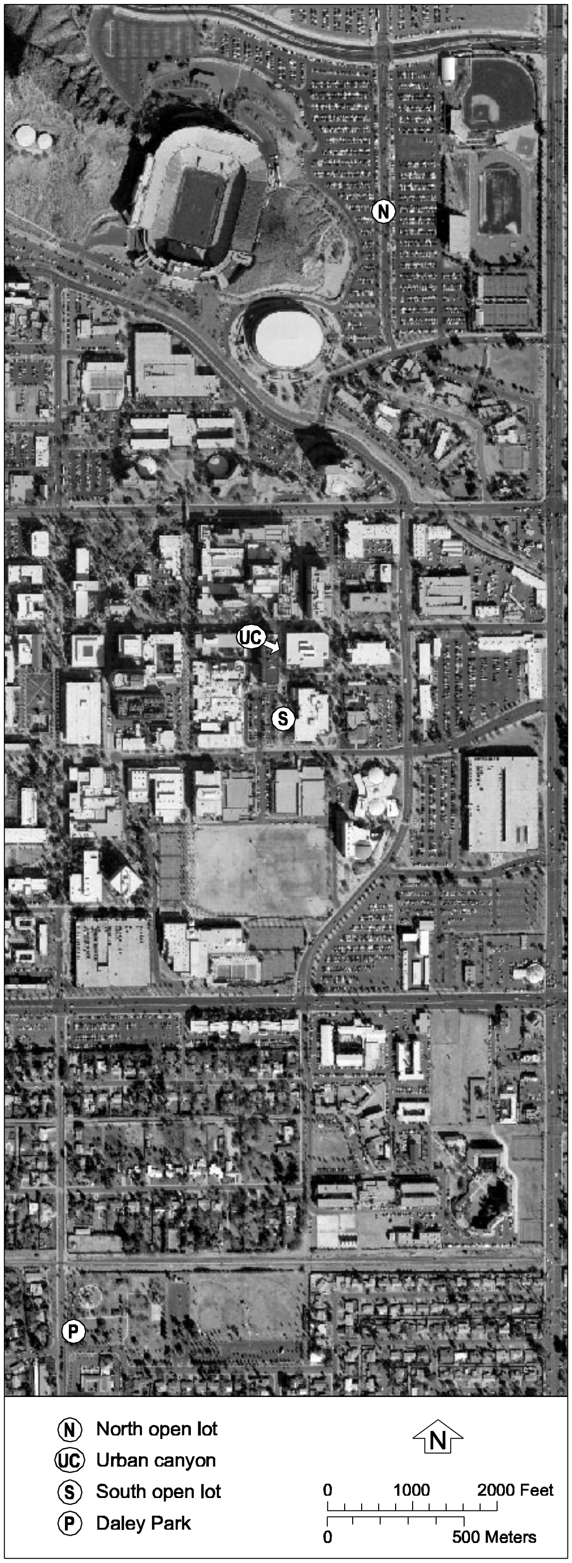

Figure 1. *Aerial photo of the ASU campus and the sites used in this study.*

more exposed sites (in this case by ca. 3°C), (b) role of surface moisture on both maximum and minimum temperatures – e.g., difference between asphalt Lot 59 site and the Daley Park site all day

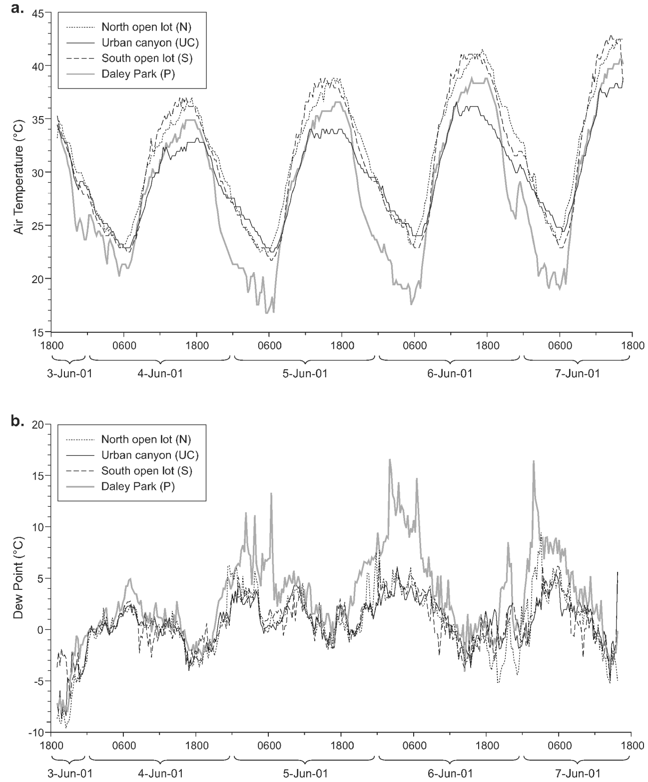

Figure 2. (a) *Five-minute data of 2-m height air temperature at the four sites,* ***(b)*** *dew points at the four sites. Note large difference in dew point between park and other cement-asphalt sites.*

(3°C cooler during day; 6°C cooler during night; and note also the dramatically higher dew points at Daley Park); and (c) warming at night in the urban canyon (UC) site relative to exposed sites by ca. 2.5°C. Since Lot 59 is similar to the smaller asphalt lot (S), we drop the smaller lot for further analysis in modeling. It should be emphasized that observations are at ground level in the urban canyon layer, or what has been called the below-canopy level (Oke 1988).

MODEL VERSUS OBSERVATIONS

We use the cooling period for the night of June 6th into the morning of June 7th to compare with model runs for the N, UC, and P sites. This is because we need to establish the 2-day preceding air temperature conditions to estimate the deep temperature at 0.25 m, as mentioned below. One of the key inputs, the sky horizon (Fig. 3), is shown for the most obstructed site, that of UC. From sky horizons, an estimate of sky view factors and the height/width ratio may be made for the canyon. Thermal admittance estimates for asphalt (Lot 59), moist soil (Daley Park), and brick building/cement material (UC) were obtained from previous literature of Goward (1981), Oke (1981), Spronken-

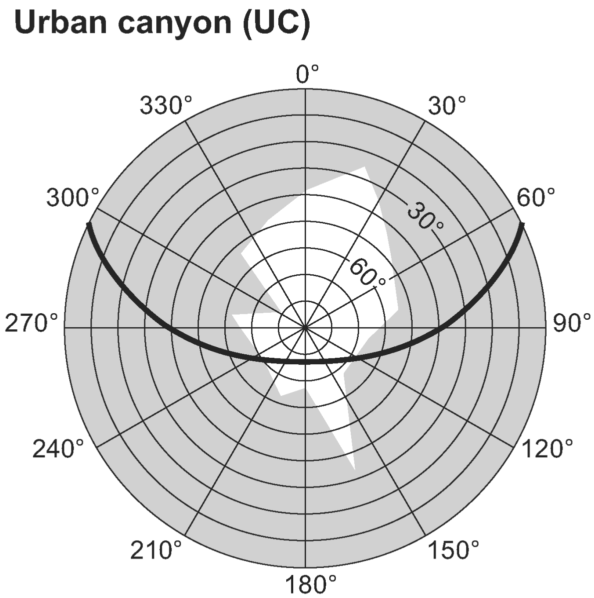

Figure 3. *Sky horizon chart for the urban canyon site. Sun path shown. White area is sky seen from within the canyon.*

Smith and Oke (1999), and Voogt and Oke (2000). We assumed an internal temperature of all buildings of 25°C and outside walls temperatures equivalent to air temperature. We used deep temperatures of the canyon floor equivalent to the mean daily air temperature for the two days prior to June 6th (a method used by Voogt and Oke 2000). We obtained an estimate of longwave incoming radiation from an ASU-City of Tempe evaporation/energy budget station atop a dam at the west end of Tempe Town Lake, in the Salt River channel just to the north of our field sites. In our case, we only have observed air temperatures from slightly above shelter height at all sites (ca. 2 m). This temperature, particularly at night, could be considerably different from SHIM's simulated radiant surface temperature (e.g., Imamura 1989, Stoll and Brazel 1992, Voogt and Oke 2000). In order to resolve this issue, we obtained hourly data from the Maricopa County Air Quality Division (B. Davis, pers. comm.). These data are available from a site <100 m from Daley Park, and from many urban-dominated sites in the Phoenix area. The temperature data at certain county sites are recorded at two levels in the atmosphere (2 m to approximately 10 m). The temperature gradient in this layer may be used to interpolate an estimate of the surface temperatures, by noting the direction of temperature increases or decreases toward the surface (lapse or inversions conditions). We use the Daley Park air quality site to correct air temperature data taken at Daley Park, and a site in downtown Phoenix over asphalt to obtain the temperature gradient to make the asphalt N site correction estimate. No correction is made for the UC site at this point, since it is likely the air is more well-mixed due to the confined space and heating from walls and the canyon floor.

Several sources of information are used to estimate the appropriateness of this procedure: (a) examination of literature on airborne-derived surface temperatures versus low level air temperatures in previous tests of SHIM (Voogt and Oke 2000), (b) review of detailed hourly 1.5 m air and radiant surface temperatures from a 70-day summer study by Stoll and Brazel (1992), and (c) analysis of data from field work and Landsat thermal data used on an NSF Human Dimensions project reported by Lougeay et al. (1996) for Phoenix.

Voogt and Oke (2000) have compared airborne radiant surface temperatures to mobile sampling of below-canopy air temperatures for summer conditions in Vancouver, B.C.; and have shown that in the rural case considerable inversions exist between the surface and air (upwards of 5°C); whereas in urban areas, the difference is much less at night and steep inversion layers are not as evident. Stoll and Brazel (1992) illustrated the same effect over a moist grass surface and commercial cement/asphalt site (gradient ca. 6°C inversion over grass and ca. 1-2°C for asphalt, for the surface to 1.5 m layer from a 70-day sample in summer).

Figure 4 illustrates for a clear night in June 1994 from the Lougeay et al. (1996) study, the progression of the temperature gradient between surface temperature and 1.5 m air temperature over the Lot 59 locale used in this study, and over an extensive moist acreage of turf near campus (just to the west of campus, not shown in Fig. 1). Note the large inversion over the grass site (in this case irrigation by sprinklers had just occurred that particular day), and the lesser gradient over the asphalt. A

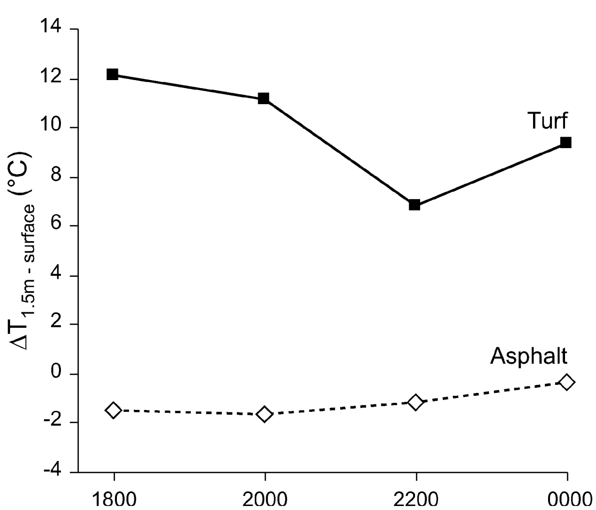

Figure 4. *Temperature difference between 1.5 m and the surface (+ values indicate inversion, - values a lapse) for asphalt and turf grass, June 23, 1992 (data from the study of Lougeay et al. 1996).*

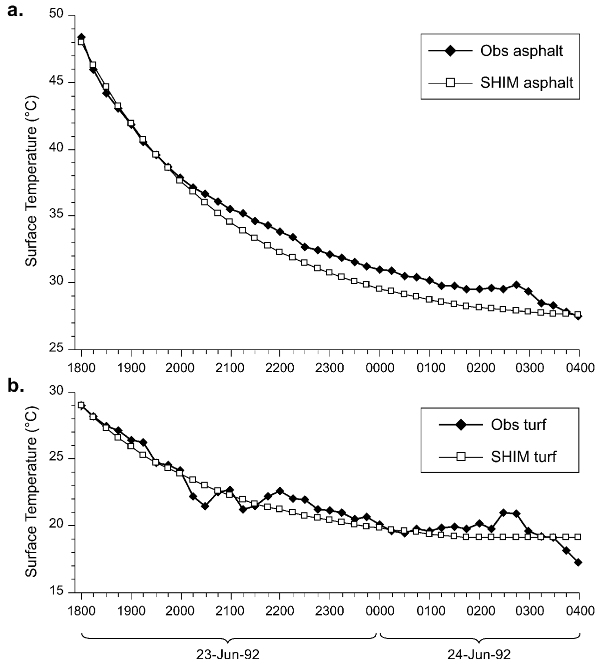

Figure 5. *SHIM simulations and observed surface temperature for asphalt and turf grass for the night of June 23-24, 1992 in Tempe, Arizona (data from the study of Lougeay et al. 1996).*

test of SHIM for these two sites shows very close correspondence, in this case with actual measured in situ surface temperatures (Fig. 5a and b).

We think it is reasonable, in the absence of remotely sensed or observed surface temperatures, which are rarely available in an urban area, to use temperature gradient adjustments to estimate a surface temperature to compare with the simulated surface temperatures. The method of assuming a gradient to adjust between surface and air temperature is acknowledged to be less than ideal. If possible, surface temperatures of the urban area ought to be continually monitored. However, in the absence of actual surface temperatures at each site to test the model for the June 6-7, 2001 period (it was not logistically feasible to do so at field sites), some adjustment is necessary, since very strong low-level surface inversions are present for some sites between shelter-height and the true surface. We simply acknowledge that the dilemma of air versus surface temperature comparisons in complex, below-canopy environments in cities indeed remains a challenging issue (e.g., Roth et al. 1989, Voogt and Oke 1998).

RESULTS OF SIMULATIONS

Figure 6 illustrates the simulations for the Lot 59 asphalt site (N), urban canyon (UC), and Daley Park (P). At UC and N, final +10 hour values in the cooling phase overnight are very close to adjusted observational values for surface temperature, even

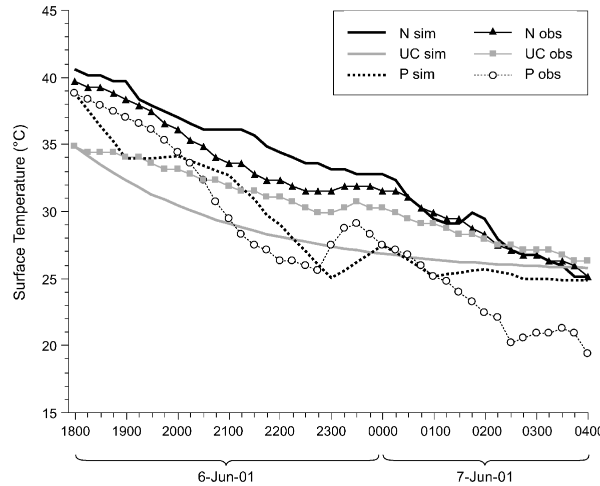

Figure 6. *Comparison of SHIM surface temperatures and observed (corrected) surface temperatures for the three sites for June 6-7, 2001. Near midnight, downvalley, easterly flow commenced across the sites and perturbed the lapse rate and induced advection.*

though in between sundown and +9 hours the rates of cooling (shape of the curve) are not identically the same. Part of the difference is that at the urban canyon (UC) we have no way of estimating an air-to-surface temperature correction at this point, and at the extensive asphalt site (N) there may be extra warm air advection unaccounted for in the model (no turbulence term is used). At Daley Park (P) there are considerable fluctuations between the model and observations, although for much of the early to mid-evening the comparison is reasonable. However, the +10 hour end temperature is off by 5°C. A possible cause of considerable model divergence from observations for much of the cooling phase is probably the evening transition of winds that is typical of clear, calm nights in Phoenix, occurring on this night at P near +6 hours after sundown, or midnight (Fernando et al. 2001, Brazel and Selover 2001). This transition perturbs the cooling phase and in SHIM is unaccounted for, per se. Inspection of hourly wind records at the air quality site near P indicated a pulse of wind from the east accompanying a downvalley passage of drainage wind flow at about midnight – just the time when divergence between the model and observations becomes largest. Post this period, cold air flow influences the site and cools the surface much more than predicted by the SHIM force-restore model.

SAMPLE OF MODEL USE FOR QUESTIONS OF URBAN CHANGE

With the aid of simulation modeling such as SHIM, one can evaluate the sensitivity of heat island processes and key variables that contribute to rapid nighttime heat island development on the landscape. Three examples are provided below that

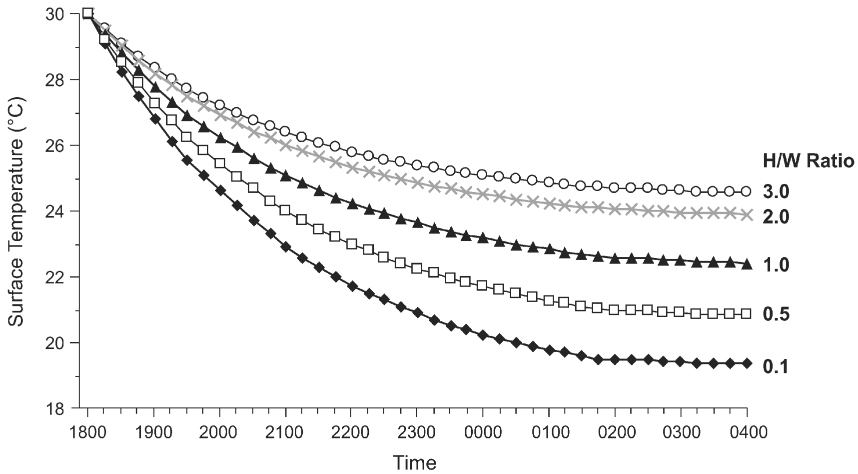

Figure 7. Simulations using SHIM for various height/width ratios of buildings (0.1 to 3.0 range) starting at temperature of 30°C at 1800 and showing the +10 hour progression of cooling.

illustrate the effects of urban canyon dimensions, surface material heating and cooling, and heat retention in the urban landscape due to variable sky view factors.

Figure 7 shows an example of cooling for +10 hours from a starting point of 30°C at 6 pm for differing heights/widths between buildings and streets (H/W), assuming a thermal admittance of 1000 $Jm^{-2}\sqrt{sec}^{-1}K^{-1}$ for all surfaces (close to values for urban landscapes). Note that if buildings are tall with narrow streets, the heat island by morning is larger by some 5°C. The worse case is to have high heat retentive materials with critical H/W values exceeding 0.5 (Oke 1981). The simulation results imply that building distributions on the landscape do not exacerbate heat islands by density alone, but by spacing between buildings in combination with heights of buildings. Recently, for example, Stone and Rodgers (2001) allude to this point using thermal remote sensing data for Atlanta, Georgia, and Crewe et al. (in review) discuss this point relative to the potentials of new urbanism landscape implementation in Phoenix.

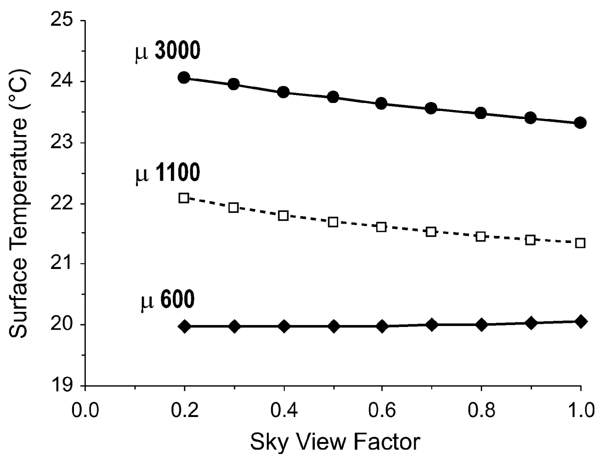

Figure 8. Simulations using SHIM combining various thermal admittance values (600, 1100, and 3000 μ) and at same time variations of sky view factors (0.0 to 1.0 - 0.0 a completely obstructed sky by buildings, etc; 1.0 a completely unobstructed horizon). Values shown are for the ending +10 hour cooling from 1800 starting point, commencing with 30°C.

Figure 8 shows, again for a starting point of 30°C at 6 pm, a combination of simulating a decreasing sky view factor (obstructing the sky more due to canopy of buildings or even trees), and at the same time changing the surface thermal admittance (μ=600 is virtually sand or some equivalent rapidly heating and cooling material; μ=1100 is asphalt; μ=3000 is a very high heat retentive substance or landscape that combines an urban canyon of heat with high heat retentive materials). The +10 hour post-sundown values are shown for combinations of thermal admittance and sky view factor. By reducing μ, no matter what the sky view factor, the urban area may cool by better than 5°C compared to heat retentive surfaces. Although inside a house the insulation is better with outside surfaces that do not conduct fast into the building (high thermal admittance materials), the outside air suffers at night due to heat retention by these materials, and produces external heat islands. The surface should have high reflectivity during the day, but rapid cooling at night to avoid the intense nighttime desert heat island. As illustrated by the Daley Park site data, the effects of water are to ameliorate daytime heating going into the cooling phase. Much literature for arid areas, however, properly focuses on low-water use species of trees to accomplish desirable shade during day time (e.g., Simpson and McPherson 1989), so that structures might start the cooling phase at lower temperatures.

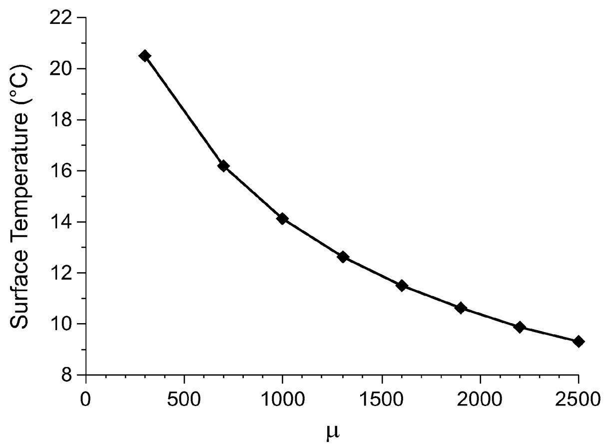

Figure 9. *The relation between +10 hour temperatures (from 30°C at hour 0) and values of μ used for the modeling of the cooling.*

Figure 9 shows, starting at 30°C at 6 pm, the +10 hours later amount of drop in temperatures at the surface for a range of thermal admittance values of materials. It results in a non-linear response, with materials that are not as heat-retentive cooling the fastest at night, more than 10°C in this example, from those materials highly heat retentive. The large thermal admittance materials such as asphalt, cement, etc. (μ>1000) do not cool as efficiently. The proportion of land cover that can be kept below μ equal to 1000, the better the overall cooling will be, in the absence of extreme effects of soil moisture cooling.

CONCLUSIONS

Urban areas have long been recognized by urban climatologists and planners as consisting of a myriad of neighborhood scale climate and ecological conditions. Ecological landscapes in the Phoenix metropolitan area have become increasingly fragmented and more structurally complex with time, as indicated by Jenerette and Wu (2001) for the period 1915-1995. Reynolds and Wu (1999), contemplating the Central Arizona–Phoenix Long-Term Ecological Research (CAP LTER) urban region, explain that ecological considerations demand an approach typified by a hierarchical patch dynamics paradigm. The implications of ecological findings for the assessment of urban climates and related planning designs are that even in urban areas with dense observational networks of historical weather and climate stations, key processes that explain the urban effects at multiple scales are not possible to fully identify with simply an empirical data approach. Some combination of remote sensing and modeling-assisted analysis, together with network data, help reveal causal mechanisms for a desert urban climate with which careful designs for the future may be made. The SHIM model appears to be a valuable aid to combine with key field observations for the study of urban ecological and climate impacts in the study of the urban ecosystem, because key variables of the human/natural ecosystem that induce local change are identified.

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