J7.3 Mitigating Urban Heat Island Effects with Water- and Energy-Sensitive Urban Designs

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Introduction

The emergence and intensification of Phoenix's urban heat island (UHI) have been well documented over the years (Hsu, 1984; Brazel et al 2007). Summer daily minimum temperatures above 32ºC were unheard of immediately after World War II when the city's growth spurt began; today they are commonplace. Higher temperatures increase the potential for heat stress, especially among vulnerable populations (Harlan et al 2006); reduce human comfort (Baker et al 2002); and limit the city's potential as a year-round tourist destination. In addition, an expanding and intensifying urban heat island raises the costs of cooling city buildings during peak-energy-use summer months and increases residential water demand (Guhathakurta & Gober, 2007). City officials have acknowledged the daunting challenges of downtown revitalization featuring mixed-use residential development and a pedestrian-oriented lifestyle in the face of increasing nighttime temperatures.

One obvious way to mitigate the UHI in Phoenix is with the use of irrigated landscape treatments—turf grasses and humid-region trees and shrubs. Evaporation from irrigated surfaces cools the scorching daytime desert temperatures and thus prevents the buildup of stored heat, a critical factor in the UHI (Grimmond and Oke, 1999). The challenge, however, in a desert city with limited water supplies lies in the tradeoffs between the temperature-reduction properties of irrigated surfaces and the water required to maintain them. The scientific and planning question is how to achieve the greatest nighttime cooling with the least water used.

In collaboration with the City of Phoenix Water Resources Department, we used a simple model of heat fluxes in urban areas, the so-called LUMPS (*Local-Scale Urban Meteorological Parameterization Scheme*), to examine the variation in temperature and evaporation at the census tract scale in 10 tracts of the urban core (Mitchell et al 2008; Grimmond & Oke, 2002).

This presentation reports on our efforts to use LUMPS to analyze the effectiveness of different planning strategies. Following the work of Mitchell et al (2008), we simulated temperature and evaporation conditions in Phoenix with an eye toward identifying the urban-design conditions that best balance nighttime temperature with water use. Our study used a set of 10 census tracts chosen to represent industrial, residential with irrigated (mesic) landscaping, and residential with native desert (xeric) landscaping.

The Study Area

The economy of urbanized Phoenix is heavily dependent upon land development and real estate construction (Gober, 2006). It is estimated that one out of every three dollars in the regional economy comes from some aspect of the home building industry, including general contractors, construction workers, architects real estate agents, mortgage loan officers, and title companies. This emphasis on growth and new construction has led to the proliferation of low-density developments at the urban fringe and to a weak central core. The City of Phoenix has been slow to develop policies to promote the downtown as the basis for community identity and as a mechanism for economic development. Furtive efforts at downtown redevelopment began in the 1970s, but were overwhelmed by the centrifugal forces of suburbanization and decentralization during the 1980s and 1990s. Serious efforts to rejuvenate the downtown are now afoot and involve the completion of a light-rail system that began operation in December, 2008; mixed-use development designed to integrate commercial, recreational, and residential uses, and a variety of publicly supported projects, including expansion of the downtown campus of Arizona State University, a biotechnology research center, an arts district, and a branch of the University of Arizona's medical school.

An intensifying UHI is incompatible with a pedestrian-oriented downtown. The City appointed an UHI Task Force in 2005 to recommend mitigation strategies. The City is

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studying and considering the use of cooler materials for use in pavements, benches, and roofing. Another option is to use irrigated vegetation as a mitigation option, but there is understandable concern about how much water will be needed for effective UHI mitigation and the viability of water versus non-water strategies.

Methods and Data

We used an urban energy balance model to simulate evaporation and temperature under different UHI-mitigation strategies for 10 census tracts chosen by city staff in and near the urban core (Fig. 1). Upon initial inspection of preliminary data from Census 2000, Maricopa County Assessor's Office and a Normalized Digital Vegetation Index (NDVI) coverage to indicate vegetation density, four sites were chosen for their industrial character (large buildings, lots of impervious surfaces, and little vegetation), three for residential characteristics with a large proportion of irrigated vegetation cover (mesic), and three for residential characteristics with little vegetative cover (xeric).

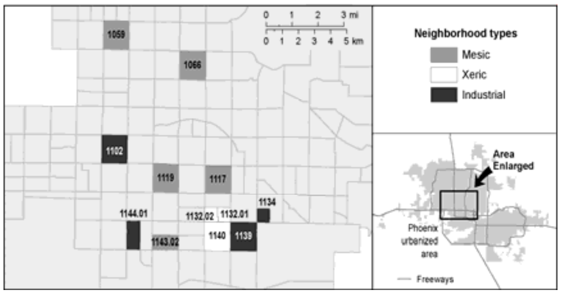

Fig. 1. Ten census tracts in the urban core of Phoenix chosen to determine LUMPS energy budget values.

As Grimmond and Oke (2002) state, the basic premise of LUMPS is that heat fluxes can be modeled using net radiation, simple information on surface cover (areas of trees, grass, water, buildings, soil, and impervious materials), morphometry (roughness element height and density), and standard weather observations (air temperature, humidity, wind speed, and pressure). LUMPS output is in the form of hourly energy budget components of latent heat, sensible heat, heat storage, and net radiation in units of W/m^2. We used LUMPS output for two additional sets of calculations. First, we used the latent heat flux converted from hourly energy units of W/m^2 to hundreds of cubic feet of water loss for the month as an indicator of evaporative loss. Secondly, we estimated the nighttime temperature cooling rates for the 10 neighborhoods through analysis of the LUMPS sensible heat flux values for the period 8:00 pm to midnight. We used as a gross estimate the expression in Mitchell et al (2008) which calculates the rate of temperature change from knowledge of the sensible cooling and boundary depth. We estimated the typical height of this shallow layer in two ways: (1) from results of Grossman-Clarke et al (2005), and (2) by iterating the height until the cooling rate magnitudes calculated were in the range experienced by cooling rates recorded from nearby hourly recording weather networks.

UHI-Mitigation Scenarios

We created three urban-design scenarios at the aggregate census tract scale (similar to LUMPS local scale) and applied them to each of the 10 census tracts using LUMPS. The *first* simulated a more compact city with more building coverage, the *second* a more vegetated oasis-like city, and the *third* a more desert city with less vegetation and more unmanaged soil. Results demonstrate that increasing building density by 10% slightly increases the rate of evaporation across all the tracts and increases monthly total outdoor water use by 8,388 ccf (6.3 million gallons) which represents 2.6% of estimated outdoor use. In this scenario, less heat is going into heat storage of impervious surfaces and soil, and the increased building density would also slightly increase the transfer rate of latent heat by creating a "rougher" surface and more 3D surface area, thus accounting for the increased water loss overall in this scenario. The reduction in soil and impervious surface area, with no change in wet fraction yields a cooling greater than the base case of between 0.35 to 0.45 ºC per hour.

Scenario 2 had the largest effect on evaporation and temperature. Adding 20% more vegetation significantly increased the evaporation rate. Although the absolute increases are higher among the heavily vegetated tracts, the percentage increases are equal, because the model uses the wet fraction to estimate latent heat flux. Scenario 2 increases the outdoor water use by 103,982 ccf (77.8 million gallons) which would increase total outdoor use in these 10 tracts by 32.8%. Adding vegetation increases nighttime cooling over the base case, especially in tracts that are not now highly vegetated. Scenario 2 produces more cooling than Scenario 1, but Scenario 1 does almost as well as Scenario 2 in the heavily vegetated tracts.

Scenario 3 simulated the effects of a major water conservation campaign aimed at reducing outdoor water use in the inner city. This scenario replaced irrigated surfaces with unmanaged soil. Model results point to a reduction in outdoor water use of 40,756 ccf (12.8% of the estimated total) at the cost of a substantial reduction in nighttime cooling in most of the tracts. The three most heavily vegetated tracts experienced smaller-than-average reductions in nighttime cooling as they maintained the minimum vegetative cover to prevent heat storage and facilitate nighttime cooling. Reducing vegetation in these three tracts accounted for more than half of the total water savings, with relatively small reductions in cooling. In the industrial and xeric tracts, Scenario 3 produced smaller water savings and larger reductions in nighttime cooling. With regard to the ratio of cooling to evaporation, the model shows that Scenarios 1 and 2 increased the efficiency of water use, while Scenario 3 reduced it. Actions to reduce impervious surfaces and to plant irrigated vegetation produced the most cooling with the least additional water. Reducing irrigated vegetation saved water but at a sizable cost in terms of nighttime cooling, especially in industrial zones and xeric residential neighborhoods. The most densely vegetated neighborhood actually gained in efficiency from reducing vegetation in Scenario 3, and the other mesic tracts experienced marginal reductions in efficiency.

Conclusions

Future research will involve a citywide analysis that can simulate the effects of different scenarios applied uniformly across the city or focused on particular neighborhoods or types of neighborhoods. The model offers potential to sort out some of the difficult interrelationships associated with UHI-mitigation, for example, in assessing the costs of increasing water use versus decreasing energy use. A spatially-informed approach using GIS for a citywide analysis would allow these energy and water costs to be related to neighborhood socio-economic characteristics and offer the opportunity to quantify the people and places most at risk (in terms of water and energy costs) of climate change in large cities.

Our own results suggest that the optimal strategy for UHI mitigation may differ from neighborhood to neighborhood and that no “blanket” mitigation approach across neighborhoods is appropriate. The LUMPS model and other models of urban heat fluxes at even finer scales offer the opportunity to explore new options for designing cities that minimize resource use and maximize social, economic, and environmental goals.

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