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URBAN HEAT ISLAND IN PHOENIX: AN EMERGENT PROPERTY OF RAPID URBANIZATION

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1. INTRODUCTION

Urbanization in the post-industrial revolution era, especially the recent rapid urban growth known as the Brown Revolution, has brought about unprecedented anthropogenic stressors that some believe may change the functioning and structure of the Earth system or a part thereof (Hunt et al. 2007). Stressors, either sustained or spasmodic, can topple the operating regime of a natural system to a new, even perhaps an undesirable, state upon exceeding certain forcing thresholds (Allenby & Fink 2005; Folke et al. 2004; Cumming & Collier 2005). One such stressor is the Urban Heat Island (UHI); it is a result of dense built infrastructure of cities that absorbs and traps solar- and traffic-generated heat and retains it for periods longer than natural surfaces because of the high heat capacity of engineered material such as concrete and asphalt. Since the early work of Oke (1982), there is mounting evidence that urban geometry and thermal properties of surface material in urban areas (i.e., land use) are the major causes of UHIs. The urban geometry is characterized by several methods: (i) the canyon (a three-dimensional space bounded by a street and the buildings that abut it) geometries, measured in terms of the building height to street width ratio; (ii) the Sky View Factor (SVF), which signifies the fraction of sky dome visible from a given outdoor point; and (iii) a “compactness index”, which is defined as the ratio of building surface area (excluding the plan area) to the surface area of a cube that has the same volume as the building. For micro-scale phenomena the urban geometry is more important, but at the meso-scale both the geometry and surface thermal characteristics play an equal role (Todhunter, 1990). Additional contributors to the UHI are anthropogenic heat (heat waste from combustion and metabolism), (ii) Urban ‘greenhouse’ effect (increased incoming long-wave radiation from polluted urban atmosphere), (iii) Evapotranspiration loss (reduction of green areas in cities lead to more sensible than latent heat transfer), and (iv) wind shelter (reduced ability of wind to carry heat either as sensible or latent turbulent heat flux.

There has also been a change of lifestyle among urban dwellers in recent times, especially in the medium and high-income groups, who spend more time indoors than outdoors (Ahmed, 2003). In the face of increasing discomfort in the outdoors, one could expect more human activities to occur indoors, which might necessitate greater use of air-conditioning, which in turn will exacerbate outdoor temperatures as excess heat is emitted to the urban air (Baker et al., 2002). Another consequence is the increase of water usage (Guhartakurta et al., 2005). This is especially problematic in hot, dry areas where water resources are scarce. Furthermore, UHIs add to the urban mortality/morbidity concerns. While heat waves in general are major health hazards, urban areas worsen these problems, even in temperate cities during hot summers. Also note that the dynamics of the cities is dependent on tightly coupled, highly sophisticated networks of infrastructure, which are vulnerable to failure and produce environmental impacts through their inherent complexities. Coupling causes new behaviors as well as new modes and mechanisms of failure and vulnerability, which are called emergent behaviors (complex outcomes from simple interactions; Watkins & Freeman 2008). UHI is one of such emergent behaviors, wherein mainly the transportation, built and energy infrastructures interact with the environment, and the results can be of undesirable environmental consequences.

The rapid urbanization in the Phoenix area since the 1950’s has created an undesirable heat island, and in some areas it is as large as 11^{o}C (Brazel et al. 2000, 2005; Emmanuel & Fernando 2007; Fernando 2008). Large, energy-intensive indoor air-conditioned spaces are common in Phoenix (Eagan 2007), which pump heat to the urban atmosphere and increase outdoor temperatures, thus creating a positive feedback on energy use. Beyond certain temperature exposure thresholds, some vegetation types are expected to disappear and airflow patterns may change, thus adversely affecting the microclimate and air quality. The UHI obviously bears upon thermal comfort of humans, whose bodies operate most efficiently in the ambient temperature range 20-27°C and humidity 35-60%. Above 35-40°C, humans are susceptible to both acute and chronic effects (fainting, heat strokes, cramps and even death) and physiological responses thereof may spur productivity loss in workplace (NIOSH 1986). UHI in Phoenix also raises *environmental justice* issues (i.e., a disproportionate share of environmental burdens that poor, disadvantaged and minority communities bear), given that tribal (American Indian) lands are located contiguous to Phoenix metropolis. These tribal nations may bear the brunt of UHI and changes of pollution transport patterns, for which they are not responsible (Watson & Overberg 2008).

Researchers at ASU are addressing Phoenix UHI issues on multiple fronts, and the work reported in this paper deals with the physical aspects of UHI development. A laboratory program was conducted to delineate the fluid mechanical scaling involved, an urbanized meso-scale model was used to better capture the UHI effects in the area and field studies were conducted to study micro-climatic aspects of the UHI.

2. SURFACE CONVERGENCE VELOCITY SCALE

The intensity of UHI is customarily expressed in terms of the characteristic temperature difference ΔT_{u-r} between the urban area T_u and its natural surroundings T_r, $\Delta T_{u-r} = T_u - T_r$, and its magnitude depends on a myriad of factors. Synoptic (regional-scale) winds cause rapid advection and mixing of air, leading to the obliteration of UHI. Areas with topographic variations (complex terrain), in addition, show significant local thermal circulation consisting of slope and valley winds (Whiteman 2000), which also affects UHI. In urban climate studies, ΔT_{u-r} is approximated by simple empirical formulae that take into account the population P (a measure of anthropogenic activities) and the background wind field U. With regard to the velocity fields induced by the UHI, consider the formation of a plume of diameter D and surface temperature T_p. The temperature of the surrounding surface is T_o. The interest here is the convergence flow near the surface (in the atmosphere, the first few tens of meters), which in general is a function of height. The governing parameters for the problem are the buoyancy of the source $g\alpha(T_p - T_o) = g\alpha\Delta T_S$, the buoyancy frequency of the background stratification N, the kinematic viscosity ν and the source diameter D. After some manipulations and simplifications, the surface convergence velocity U_r can be written as

$$\frac{U_r}{\left(g\alpha\Delta T_{u-r}D\right)^{1/2}} = f\left\{\frac{\left(g\alpha\Delta T_{u-r}D\right)^{1/2}D}{\nu}\right\}. \quad (1)$$

A laboratory experiment was conducted to study the validity of (1) by heating an isolated patch of the bottom of a tank of diameter D, and the results are shown in Figure 1. The results confirm the convergence velocity scale $U_r = (g\alpha\Delta T_{u-r}D)^{1/2}$, and with a proportionality constant of about 0.08 the absolute convergence velocity can be estimated.

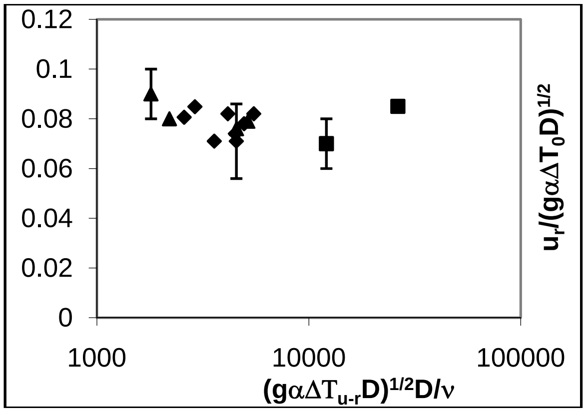

Figure 1: A plot of the proposed convergence velocity scale $(g\alpha\Delta T_{u-r}D)^{1/2}$ as a function of the pertinent Reynolds number $(g\alpha\Delta T_{u-r}D)^{1/2}D/\nu$.

3. PREDICTION OF UHI ON THE MESO-SCALE

Conventional meso-scale models treat urban areas with one or a few land-use classes, which are inadequate to capture details of processes occurring near the ground, especially in the urban roughness surface layer. Most conventional models specify urban elements using the roughness approach, where the Monin-Obukhov theory is used to specify heat and momentum fluxes in the surface layer. Nevertheless, conditions near an urban surface are far removed from that required for the MO theory to be valid. To remedy this, the Drag Approach has been advanced (Dupont et al. 2004), where the urban influence is specified by a modified momentum, energy and turbulence equations, while paying lesser regard to MO parameterizations. As a part of our work, an urbanized version of the meso-scale model MM5 developed by DuPont et al. (2004) (MM5-U) was employed. This model was evaluated against data taken from the Phoenix area, during three field campaigns conducted in 2001, 2006 and 2007. Some of the parameterization issues of MM5-U were identified and new parameterizations were proposed to produce the MM5-U (ASU).

The essentials of MM5-U are the implementation of a DA-based roughness parameterization in the GSPBL scheme. The turbulence parameterizations were changed to account for roughness-induced turbulence and the heat and momentum diffusivities are assumed the same. A 3D soil model SM-U (3D) was introduced to take into account the heat fluxes, including anthropogenic heat flux, and surface temperature in canopy grid cells. In the MM5-U (ASU) version, a new turbulence lengthscale and momentum diffusivity were introduced, momentum and heat exchange coefficients for stable periods were modified, an evening transition parameterization was implemented for the cases of low synoptic flow and the roughness length was modified.

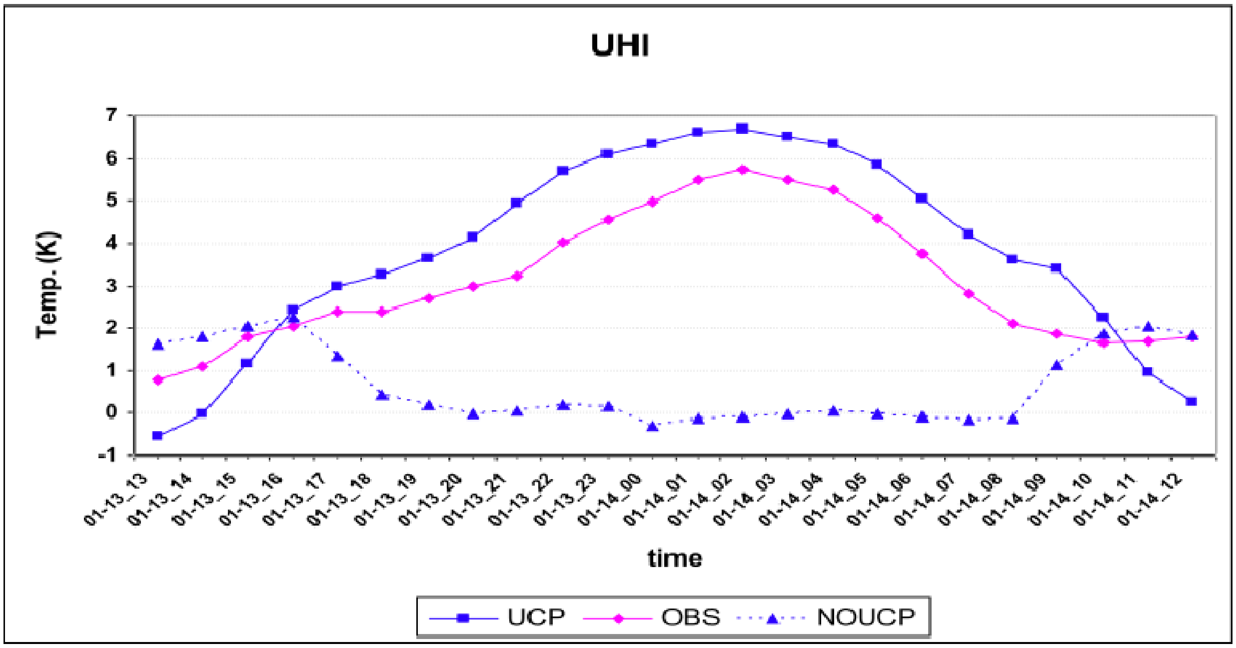

Figure 2: Computation of UHI (urban-rural temperature difference) using conventional MM5 (noUCP) and with MM5-U (UCP version). Key for abscissa: 1-13-13 indicates January 13th 2006 at 1pm or 13hr. Obs – Observations. Note the urbanized model captures the UHI well.

The conventional MM5 (Dudhia 1993), MM5-U and MM5-U (ASU) were evaluated against the data, and the performance statistics indicated that the latter performs better for the case considered with respect to temperature and sensible heat flux predictions. The heat island was well captured (Figure 2). Nevertheless, the performances of two models with respect to the wind speed and momentum flux were almost similar. The MM5-U and MM5-U (ASU) were then evaluated against data, and the latter showed significant improvements in the predictions of momentum and heat fluxes, wind speed, wind direction and temperature. In all, statistical measures indicate that MM5-U (ASU) performs better than its predecessors MM5 and MM5-U for the case of meteorological predictions of Phoenix. Further refining of sub-grid parameterizations and evaluations against more extensive data sets are necessary to establish MM5-U(ASU) as a tool for general applications. In addition, utilization of satellite data is recommended to validate the skin temperature predictions as well as obtaining high-resolution land-use/land-cover information.

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