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Scaling of the urban heat island intensity using time-dependent energy balance

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ABSTRACT

The urban heat island intensity (UHI) can be scaled with the urban length scale and the wind speed, through the time-dependent energy balance. The heating of the urban surfaces during the day-time sets the initial temperature, and this overheating is dissipated during the night-time through mean convection motion over the urban surface. The energy balance shows that this cooling effect can be quantified in an exponential decay in time. The minimum temperature reached at the end of this cooling period corresponds to the UHI, which increases with increasing urban length scale and decreasing wind speed. The temporal data for Phoenix, Arizona are reasonably accurately traced by this model, for the time period, from 1983 to 2010 during which Phoenix has undergone substantial expansion and therefore an increase in the urban length scale. Comparisons with the data in several cities around the world also yield quantitatively correct results for the effect of the wind speed. This model does require one correction factor to account for different urban topology in different cities. Thus, using a small number of readily available data for the urban length scale and the wind speed, the UHI intensity can be described with possible predictions for future trends.

1. Introduction

There have been many studies on the causes and impact of the heat island effect (e.g. Baker et al., 2000, 2002; Christy et al., 2006; De Laat and Maurellis, 2006; Kalnay and Cai, 2003; Pearlmutter and

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Berliner, 1998; Rydin, 1992; Stone and Rogers, 2001; Oke, 1973). A wide range of causes have been attributed, including the land surface energy balance (or imbalance) due to urbanized land surface and built structures, anthropogenic heat release and different atmospheric constituents over the city (Landsberg, 1975; Sailor, 2011). While the significance of the urban heat island effect is universally recognized (Arnfield, 2003; Chow et al., 2012), the approaches to its understanding and mitigation are quite varied, ranging from simple "slab" approach (Grimmond et al., 1991) to sophisticated models that resolve urban canopy physics (Chen et al., 2011; Wang et al., 2011). One of the important aspects is quantifying the magnitude of the urban heat island effect in terms of relevant variables, which again vary widely depending on the authors. A key step in this quantification is "scaling", i.e. developing a functional relationship between the urban heat island effect and causal variables. The urban heat island intensity (UHI) is typically the departure from the undisturbed temperature, although the definition of the "undisturbed" often is not clarified.

Many authors have contributed toward this scaling approach. The most consensual one appears to be the one based on the steady-state convection of the thermal boundary layer over the urban surface. This work is credited to Summers (1964), and has been used by many authors in computational and experimental studies (Uno et al., 1988, Rydin, 1992; Richiardone and Brusasca, 1989; Raman and Cermak, 1975; Lu et al., 1997a,b; Cenedese and Monti, 2003). In this scaling, the horizontal (*x*-direction) convection is balanced by vertical (*z*-direction) heat flux term. This steady-state energy balance results in an estimate of the urban heat island intensity, expressed as the temperature difference with respect to the "surrounding" area.

$$\Delta T = T_u - T_r = \left(\frac{2H_o \gamma \chi}{\rho c_p U_m}\right)^{1/2} \tag{1}$$

T_u is the urban temperature, and T_r, the rural (surrounding) temperature. H_o is the surface heat flux, γ the potential temperature gradient in the approach flow in the vertical direction, ρ the air density, c_p specific heat, and U_m layer-averaged wind speed.

Two comments can be made concerning this result. First, it is based on steady-state heat balance. As shown in Fig. 1 the urban temperature is certainly not steady-state. In some laboratory experiments, it takes hours for the steady-state conditions to be achieved in scaled-down convection currents. As seen in Fig. 1, the time scale of the energy exchange is also measured in hours, where the "nighttime" minimum temperature is reached just before sunrise hours between 6 and 7 AM. In

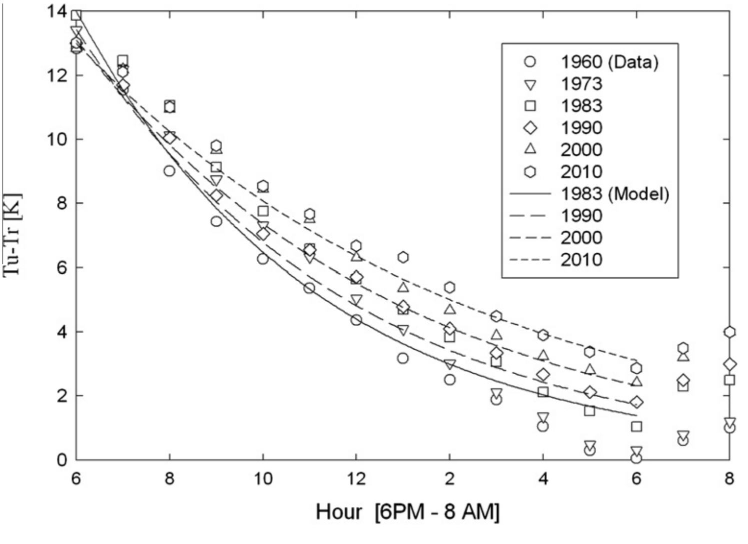

Fig. 1. Temperature decay as a function of time, in Phoenix, AZ for years 1960–2010.