J12.5 ESTIMATING THERMAL RESPONSIVENESS OF LOCAL-SCALE CLIMATE ‘ZONES’ WITH A NUMERICAL MODELING APPROACH

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1. INTRODUCTION

The diversity of ‘urban’ and ‘rural’ landscapes at the local scale suggests that a more nuanced definition of the urban heat island is appropriate. Stewart and Oke (2009) propose “thermal climate zones” (TCZs) to standardize the classification and intercomparison of local scale near-surface thermal climates. Classification is based on the capacity of a site to modify its thermal microclimate. This capacity is due to its particular mix of radiative, thermal, roughness, moisture and anthropogenic properties. The objective of the present work is to estimate this capacity for several TCZs, in particular the “urban” zones.

Estimating the thermal responsiveness of the TCZs is achieved through an appropriate combination of numerical models and a set of input properties considered typical for each zone. Thermal responsiveness is considered here as the diurnal range of the urban canopy layer (UCL) air temperature. We couple the Town Energy Balance (TEB) urban surface scheme of Masson (2000) with an updated version of the K-profile column model of Troen and Mahrt (1986) to simulate TCZ energy balances at a latitude of 47.6 °N during a 48-hour period at the end of May. The modeling approach and simulation design are described next, followed by some preliminary results and, finally, a brief discussion of future work.

2. CLASSIFICATION SCHEME DESIGN

The local-scale (~ 1 km) landscape is classified firstly into four “series” —City, Agricultural, Natural, and Mixed—based on the extent to which it has been disturbed by human (cultural) activity, and secondly into “zones” based on distinguishing properties of surface geometry and cover. The numerical modeling begun here allows us to rank the zones by thermal responsiveness, and ultimately to improve the logical structure of the TCZ classification system.

Prototype “thermal climate zones” for the City series are shown in Figure 2. This classification is designed to cover all local-scale landscapes documented in modern observational urban heat island (UHI) literature (1950 and present). The reader is referred to Stewart and Oke (2009) for more details behind the rationale and development of the TCZ scheme.

3. MODELING APPROACH

The combination of models from Krayenhoff and Voogt (2004; hereafter KV04) provides a simple but relatively complete description of the boundary layer and surface radiative, heat, moisture and momentum exchanges for clear sky conditions. The Oregon State University (OSU) boundary layer model (Troen and Mahrt 1986) parameterizes mixing within the boundary layer, while the Town Energy Balance model (TEB; Masson 2000) and the soil-vegetation scheme of Mahrt and Pan (1984) (MP84) parameterize surface and sub-surface interactions for urban and natural surfaces, respectively. The Roach and Slingo (1979) 5-band longwave scheme (RS79) accounts for longwave exchanges and longwave cooling within the atmosphere. A simple broadband scheme based on Iqbal (1983) parameterizes the incoming direct and diffuse solar radiation at the urban surface. TEB is updated to include the modifications described in Masson *et al*. (2002) and Lemonsu *et al*. (2004).

OSU uses a simple 1-D K-profile parameterization of mixing during unstable conditions. The inclusion of a countergradient term accounts for non-local mixing during convective conditions. Additionally, it mixes momentum given a mean geostrophic wind speed, and it requires an input profile of large-scale subsidence in order to maintain the capping inversion and reasonable boundary layer heights.

Surface boundary conditions to the OSU boundary layer model are supplied by TEB and MP84 for urban and natural areas, respectively. Both schemes require temperature, wind speed and mixing ratio at the lowest OSU model level, in addition to longwave flux from RS79 and solar radiation, as input. They output sensible heat, latent heat, and momentum fluxes to OSU, weighted by the urban and natural fractions. Thus, OSU surface boundary conditions and eddy diffusivities are dependent on weighted average surface scheme output fluxes and temperatures.

MP84 is run as a simple 3-layer soil model with a single vegetation layer, and accounts for evapotranspiration and thermal and water storage. The most appropriate way to include UCL vegetation in the model remains a significant question. In KV04, MP84 is assumed to absorb, reflect, and emit radiation as if it was on the canyon floor, but is otherwise treated independently from TEB (i.e., in terms of its convective interactions with OSU). This approach is also taken here, but future work will more fully incorporate vegetation into the street canyon.

Advection can be a large, even dominant term in the energy budget of the boundary layer, particularly where substantial horizontal gradients exist, for example near urban-rural boundaries. Advection may be simulated by assuming that the rural simulation provides a reasonable approximation to the atmospheric profile upstream of the city from any given direction (e.g. KV04). However, advection will be ignored in the present work. This serves to maximize the influence of

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land cover on the modeled UCL thermal regime. As a result, the modeled UCL regime is an estimate of the *maximum* diurnal thermal range. Given that the primary objective is the ranking of the thermal responsiveness of urban climate zones relative to each other, the absolute value of the UCL diurnal thermal range is of less importance.

The model setup as described above was shown in KV04 to perform well against observational data obtained during the BUBBLE campaign (Rotach *et al.* 2004) at the Basel Sperrstrasse site.

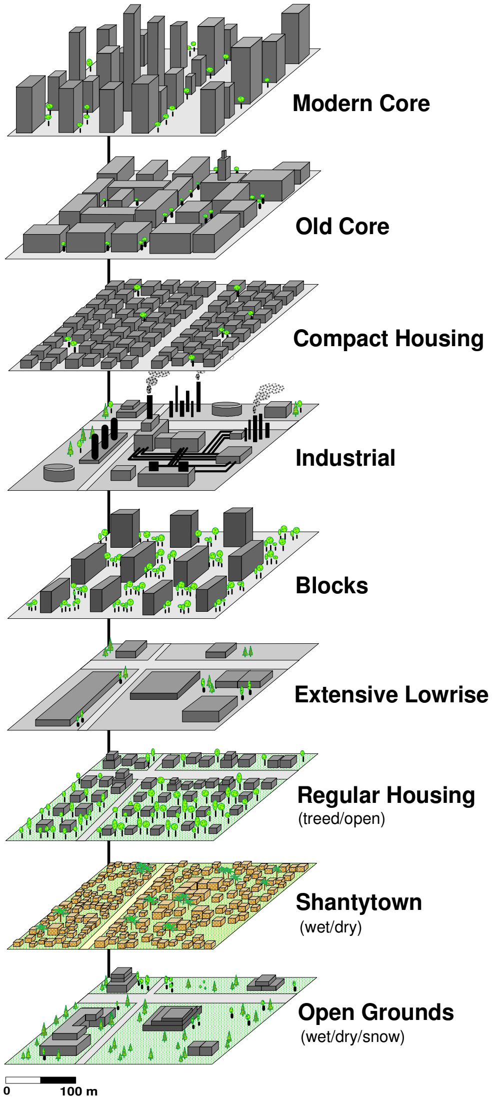

Figure 1: Prototype thermal climate zones in the City series (source: Stewart and Oke, 2009).

3. SIMULATION DEVELOPMENT

Land cover, geometric, radiative and thermal parameters necessary as inputs to the models were arrived at through an extensive search for “urban” and “rural” site parameters in the modeling and observational climate literature, We relied on our experience and judgment to screen these values and, where necessary, to estimate new values. Every attempt was made to ensure that the input values represent each zone in an ‘average’ sense. While uncertainties in parameter values remain they are likely to be overshadowed by the thermally significant variation in land cover that is nevertheless classified within a given TCZ.

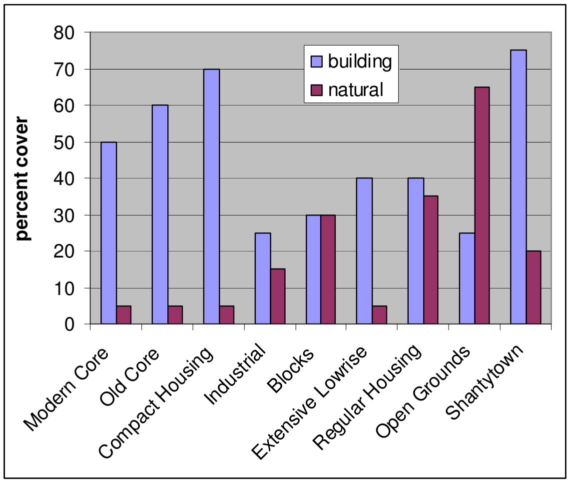

Figure 2: Percent plan area cover of buildings (roofs) and natural areas (vegetation) for the nine City zones. The remaining fraction is road.

Figures 2, 3 and 4 show preliminary values of several key parameters used in the present modeling study. The City zones are ordered from left to right in ascending order of anticipated thermal responsiveness. With several exceptions, the general trend is decreasing building size, density and massiveness (in terms of wall and roof thickness, not shown), and associated decreases in roughness, canyon H/W and anthropogenic heat.

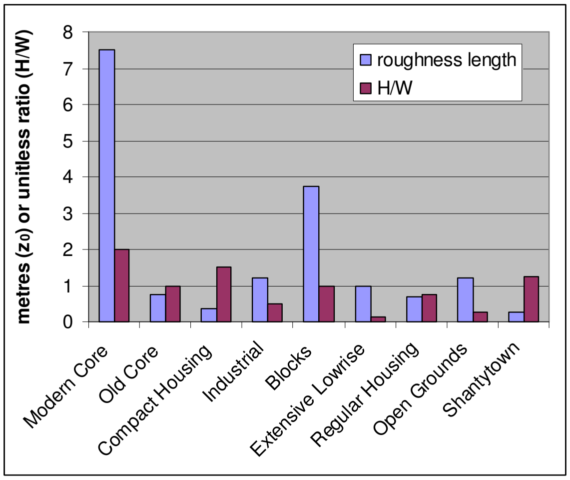

Figure 3: Mean height-to-width ratio and roughness length for the nine City zones.

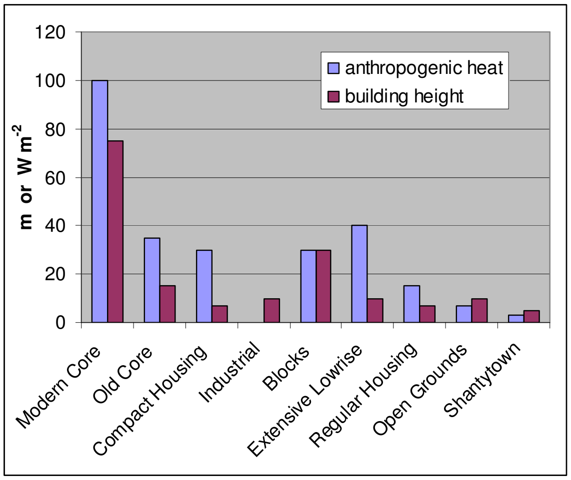

Figure 4: Mean building height and anthropogenic heat for the nine City zones. Industrial anthropogenic heat (400 W m^{-2}) is not shown so as to preserve appropriate y-axis scale.

The diurnal variation of anthropogenic heating is that of Chicago from Sailor and Lu (2004), scaled to yield the mean diurnal anthropogenic heat input indicated by Figure 4. An unchanging anthropogenic heat output was considered to be more realistic for the Industrial zone.

A 48-hour clear sky period beginning at 0000 LST May 30, 2002 is modeled. Initial profiles of temperature, mixing ratio and wind speed are based on radiosonde measurements made near Basel, Switzerland as described in KV04. Initial surface temperatures are from KV04.

4. RESULTS AND DISCUSSION

The model is run through the first day's full heating cycle in order to minimize the influence of initial conditions. The subsequent magnitude of canyon temperature evening and nocturnal cooling and daytime heating are then assessed (the period ~ 1600 LST May 30 to ~ 1600 LST May 31). As the modeled scenario has significant insolation and no advection, the daytime heating exceeds the nocturnal cooling and the model heats up on a diurnal time scale (note that net positive diurnal heat storage during periods of greater solar insolation is present in observations, such as Christen and Vogt [2004] Figure 10). As a result, we average the magnitudes of cooling and heating to obtain an average diurnal range of canopy temperature, i.e. an estimate of the thermal responsiveness, for each TCZ (Figure 5). The predicted trend of increasing thermal responsiveness appears to be supported in general.

It is important to note that the diurnal ranges in Figure 5 are specific to the solar forcing regime (latitude, day of year, sky condition) and initial boundary layer profile. Furthermore, Figure 5 includes only zones from the City series of the Stewart and Oke (2009) classification scheme, and does not attempt to quantify a representative UCL heat island but rather intra- and inter-city variation (i.e. between zones in a given city or between similar zones in different cities under the same input conditions). Estimation of "relative" heat island magnitudes awaits the simulation of thermal responsiveness in the remaining Agricultural, Natural and Mixed zones. These zones present an additional complexity in that they are expected to vary more significantly with season than the City series.

Figure 5 represents an initial attempt to quantify the thermal responsiveness of the City TCZs with little modification to a pre-existing modeling tool (Krayenhoff and Voogt 2004). Further work will focus on model development and evaluation to better include the effects of vegetation on canyon air temperature, to assess the fidelity of the modeled nocturnal urban boundary layer, and to determine the impacts of advection, wind and solar insolation (season and latitude) on the canopy air temperature.

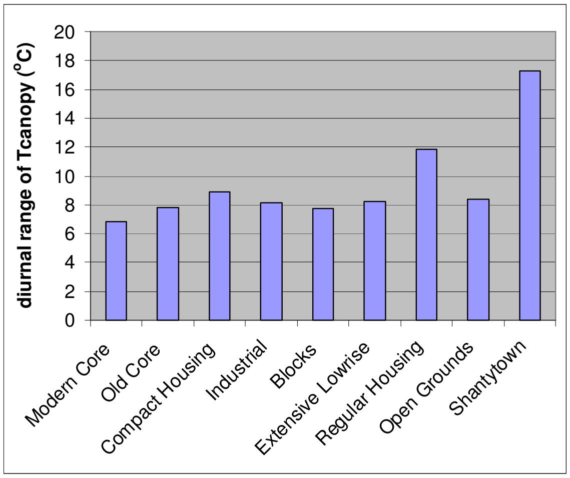

Figure 5: Modeled diurnal canopy layer temperature range for the nine City zones.

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