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NEWLY DEVELOPED "THERMAL CLIMATE ZONES" FOR DEFINING AND MEASURING URBAN HEAT ISLAND MAGNITIDUE IN THE CANOPY LAYER

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1. INTRODUCTION

Urban heat island (UHI) magnitude is the most widely recognized indicator of city climate modification in the environmental sciences. Understood broadly as a nocturnal "urban-rural" air temperature difference at screen height, UHI magnitude has been measured and reported in thousands of cities and towns worldwide since the early 1900s. The popular use of this indicator, however, has created considerable confusion in climate literature over the dichotomous classification of measurement sites—as "urban" or "rural"—thereby defining heat island magnitude. This confusion stems from UHI investigators relying intuitively on standard dictionary meanings of "urban" and "rural" to describe and classify their sites. Over time, complacency with these meanings has blurred the physical and cultural peculiarities of the "urban" and "rural" sites chosen by investigators to quantify UHI magnitude. The need for methodological rigor behind computations of UHI magnitude is now a pressing concern. We address this issue through a new and more purposeful classification of "urban" and "rural" measurement sites.

2. THE URBAN-RURAL DICHOTOMY

The urban-rural dichotomy is well-entrenched in UHI methodology: investigators routinely design, interpret, and report their observations with reference only to "urban" and "rural" measurement sites and temperature differences. Our background research suggests that one-third of empirical UHI literature gives no quantitative or qualitative description of the measurement sites defining UHI magnitude, other than to pronounce them sufficiently "urban" or "rural." Two-thirds of the literature gives only qualitative description, still without any measurable indicators of the site properties directly influencing UHI magnitude—namely, surface geometry, exposure, or cover.** In response to the incomplete and inconsistent reporting of measurement sites in UHI literature, we argue in a previous paper that spatial models of settlement growth and urban form should underpin a new local-scale, thermal climate–based landscape classification system (Stewart and Oke, 2006). This system should be anchored not by subjective or dichotomous assessments of sites as either "urban" or "rural," but by objective, measurable surface properties that directly impact screen-level temperature.

Lowry (1977) began the process of dissecting the urban-rural dichotomy into more useful parts for urban climatologists. Through that process came the notion of "preurban" temperatures (or measurement sites). Lowry defines "preurban" as representative not of urban or rural *space*, but of a *time* before human disturbance to the land. With city-based temperature records rarely predating cities themselves, Lowry allows that temperatures from modern preurban space (i.e., land adjacent to the city yet still in native condition) are reasonably analogous to those of preurban times. Lowry's framework provides only the beginning of a more involved characterization and classification of measurement space that is now needed in the study of urban climates and, more critically, urban heat islands.

3. DEVELOPING A LANDSCAPE CLASSIFICATION SYSTEM FOR UHI OBSERVATION

3.1 *Background*

Few local-scale landscape classification systems exist in urban climate literature. In 1978, Auer proposed a classification system for the city of St. Louis, USA, using criteria of land use and vegetative cover. Ellefsen (1990/1) later devised a system of neighbourhood-scale "urban terrain zones" (UTZ) based on the building morphology, street configuration, and construction materials of large U.S. cities. Davenport *et al.* (2000) developed an aerodynamic roughness classification of urban and rural terrain based on the height and density of surface elements (e.g., buildings, trees, crops). Most recently, Oke (2004) designed a simple urban-based climate classification system for the World Meteorological Organization. Incorporating features of both Auer's and Ellefsen's zones, his system divides urbanized terrain into discrete, homogenous regions called "urban climate zones." The zones are distinguished on their ability—as determined by aerodynamic roughness, mean aspect ratio, and impermeable surface coverage—to modify the local surface climate.

National land-cover and land-use classification systems are often used for UHI site characterization. The U.S. National Land Cover Dataset (NLDC), for example, divides the coterminous United States into sixteen different land-cover classes (Homer *et al.*, 2007). While impressive for its 30-m spatial resolution, the NLDC is less impressive for its representation of the urban environment. Just four of sixteen categories are "urban-oriented," with each category distinguished primarily on surface imperviousness alone. The "urban" detail in this system is clearly not sufficient to delimit

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** These results are based on review of 180 observational UHI studies published between 1950 and 2007.

and characterize city micro- and local-scale surface climates.

The scale, scope, intent, and criteria of the foregoing classification systems are variably, even poorly, aligned with those of UHI observation. The systems do, however, provide the structural and conceptual groundwork for a classification system of this intent. We therefore distill from other systems the desirable and relevant features amenable to this aim. In doing so, we recognize that all classifications face compromises and limitations. For example, the existing systems are generally unbalanced in their portrayal of urban and rural landscapes. A system without proportional representation of the city and the country is not well suited to UHI observation. The systems are also predisposed to the form and function of modern, developed cities. Their use in diverse cultural and economic regions is arguably limited.

UHI investigators also cite census population data as a criterion for "urban" and "rural" site classification. Population data, however, are not well correlated with the immediate surface geometry, exposure, or cover of most measurement sites. "Urban" and "rural" temperature comparisons on the basis of population give misleading and often erroneous estimates of UHI magnitude. Other precedents for "urban" and "rural" site classification include satellite-derived vegetation indices (e.g., NDVI) and night-light frequency data. Like population data, these indices convey little of the detailed micro- and local-scale surface conditions known to influence screen-level air temperatures. Computations of UHI magnitude are therefore not well served by population or satellite-derived metadata.

3.2 *Classification Criteria*

In theory, all classification systems should facilitate information transfer through simple and logical nomenclature. Classes and subclasses are then easily named, and generalizations later made of the members belonging to each class (Grigg, 1965). We offer additional criteria that are more contextual to the classification of UHI measurement sites:

1. *Accessibility:* the new system must be universal in function and manageable in size, especially to users with limited resources for classifying UHI sites or for carrying out sophisticated observational programs.
2. *Objectivity:* the new system must incorporate measurable and testable class properties that are relevant to surface thermal climate.
3. *Inclusiveness:* the new system must be sufficiently generic in its representation of local landscapes, so as not to inherit regional or cultural biases.
4. *Standardization:* the new system must be consistent in its representation of local landscapes and their surface properties, so as not to forestall universal recognition or acceptance of the system.

3.3 *Data Sources*

The primary source of data behind the design and rationale of the new classification system is the observational UHI literature, 1950 to 2007. Given the historical and geographical breadth of this literature, we relied on a representative sample of 180 studies. Each study was selected on strict eligibility criteria. The classification systems of Ellefsen (1990/1), Davenport *et al.* (2000), and Oke (2004) provide further support for developing the system and estimating its radiative, thermal, moisture, and aerodynamic class properties. Other sources include "urban" and "rural" site data retrieved from urban climate computer modeling studies (e.g., Lemonsu *et al*., 2004), measurement studies (e.g., Oguntoyinbo, 1970), general texts of physical climatology, remote sensing, and soil science, and from reviews of empirical urban climate literature (e.g., Wieringa, 1993; Grimmond and Oke, 1999). Lastly, literature on urban morphology was consulted for its regional descriptions and vivid illustrations of city form worldwide (e.g., Brunn and Williams, 1983; Kostof, 1991).

3.4 *Definition by Logical Division*

Scientific classification is effectively a process of definition (Black, 1952). It begins with the logical division of a "universe" class, which is then divided into a hierarchy of sub-classes on the basis of differentiating principles, or "differentiae." The end-product is a system of names for groups of classes showing regular properties. "Landscape" is taken here to be the universe class for logical division. It is defined by *Oxford English Dictionary* as "a tract of land with its distinguishing characteristics and features, especially considered as a product of modifying processes and agents." "Landscape" is for our purposes a *local-scale* tract (i.e., 100s of metres) with physical *and* cultural characteristics.

We divide "landscape" first on the principle of surface disturbance, that is, the degree to which a *cultural* imprint is superimposed on the *physical* surface. By "cultural imprint" we mean the replacement of the native surface cover (e.g., forests, grasses, soils) with a non-native cover (e.g., buildings, roads, crops). Division of the landscape on this principle yields four subclasses: city, agricultural, natural, and mixed (Figure 1).

"City" landscapes are heavily disturbed by the construction of buildings and roads; "agricultural" landscapes are disturbed by the cultivation of soils, the production of crops or forests, and animal husbandry; and "natural" landscapes remain undisturbed by the preservation of a native surface cover. A fourth class representing the "mixing" of city, agricultural, and natural characteristics of the landscape is also added to the hierarchy. The diversity of landscapes across these four classes makes their division one of degree rather than kind.

We now divide the city, agricultural, and natural classes on their micro-scale (10s to 100s of metres) surface properties relevant to canopy-layer thermal climate. These characteristics (and their classes) include (1) surface roughness height (high, medium, or low), which influences flow regimes above ground; (2) impervious surface fraction (high or low), which

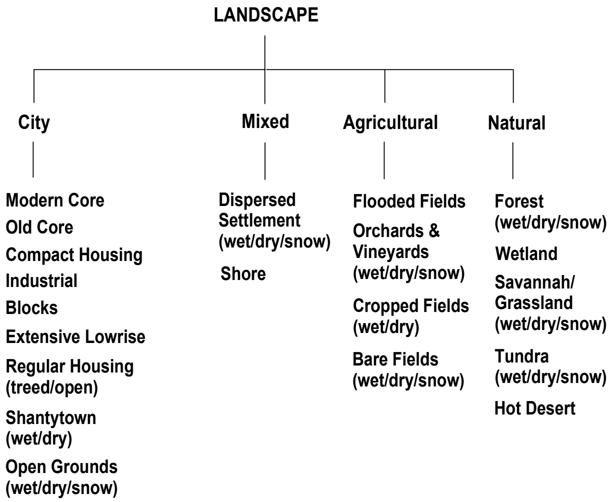


Figure 1: Logical division of the universe class.

partitions energy into sensible (heating) and latent (cooling) forms; (3) sky view factor (high or low), which influences surface radiational cooling; (4) thermal admittance (high or low), which modulates heating and cooling cycles of soils and construction materials, (5) albedo (high or low), which influences surface heat absorption, and (6) anthropogenic heat flux (high, low, or nil), which contributes combustion heat to the surface energy balance.

Finally, we group the individuals of the universe class into appropriate levels of the hierarchy. The universe class includes only those local-scale landscapes portrayed in the UHI literature sample. Differentiation of the landscape universe by each of the aforementioned surface characteristics (and their classes) is largely redundant because many of the combinations of characteristics that arise through logical division do not exist in the real world. Those combinations that do exist are retained in the system and create distinguishable classes.

By the rubric of logical division, a downtown high-rise site, for example, should be classified first as "city" on the principle of surface disturbance. Then, on principles of micro-scale surface thermal climate, the site is classified as "high" roughness, "high" impervious fraction, "low" sky view factor, "low" thermal admittance, "low" albedo, and "high" anthropogenic heat flux. A simple name (such as "modern core") should then be assigned to that class of properties. A light industrial/warehouse site follows a similar path through the landscape hierarchy, except for its placement into the "low" surface roughness, "high" sky view, and "low" anthropogenic heat flux classes. Sites that, by definition, do not qualify as "city," "agricultural," or "natural" are placed into the "mixed" class.

4. THERMAL CLIMATE ZONES

The individual landscapes found in the UHI literature sample were ultimately grouped into twenty subclasses, or "zones," by logical division of the city, agricultural, natural, and mixed classes, or "series." The names of the twenty prototype zones are given in Figure 1. "Thermal climate zones" are defined as local-scale regions of relatively homogeneous air temperature in the canopy layer. Each zone is identified by a distinguishing set of radiative, thermal, moisture, and geometric properties.

The city series is the largest in the classification system, comprising nine thermal climate zones (Figure 2). Most landscapes and measurement sites described as "urban" in UHI literature correspond with the city series. From "modern core" to "open grounds," the city series is characteristically diverse in surface roughness, impervious fraction, thermal admittance, sky view, and anthropogenic heat flux. Zones with an abundance of natural surfaces are further divided into wet, dry, and snow-cover cases. Excluding the "industrial," "blocks," and "shantytown" zones, the city series closely resembles Oke's (2004) Urban Climate Zones.

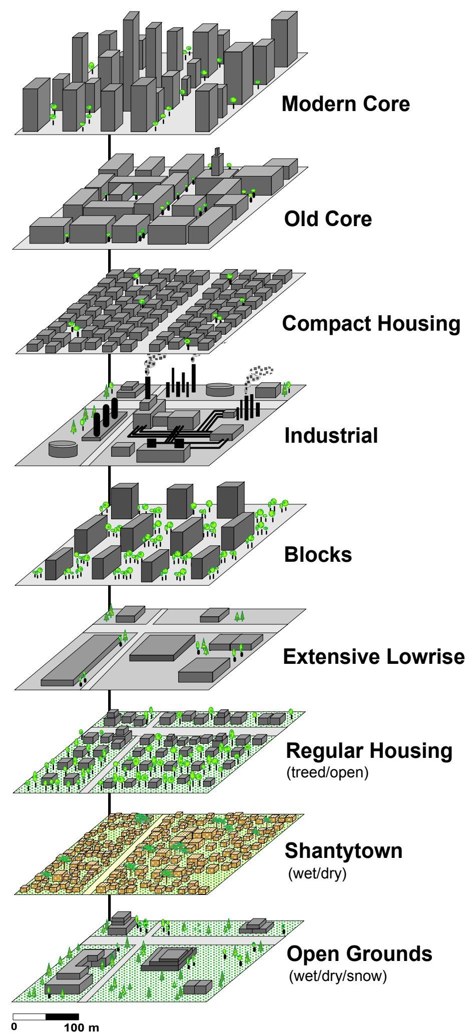


Figure 2: Thermal climate zones in the city series.

The agricultural series comprises four thermal climate zones (Figure 3). Most "rural" sites in the UHI literature are agricultural in character, but are often portrayed indiscriminately as "farmland" or "greenfields." In general, agricultural zones have an abundance of natural (though not necessarily native) surface cover, few paved roads or scattered dwellings, and sky view factors at or near unity. The property with greatest variability in the agricultural series is surface thermal admittance, which is high in "flooded fields" but low in (dry) "bare fields." Several of the agricultural zones are subdivided by wet, dry, and snow-cover cases.

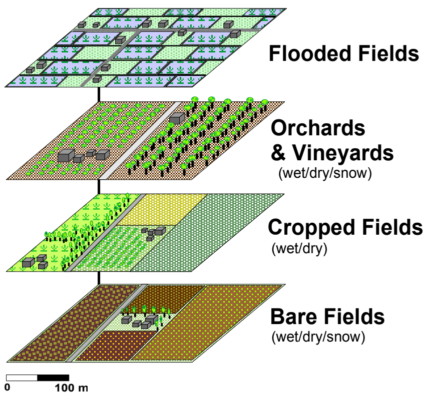


Figure 3: Thermal climate zones in the agricultural series.

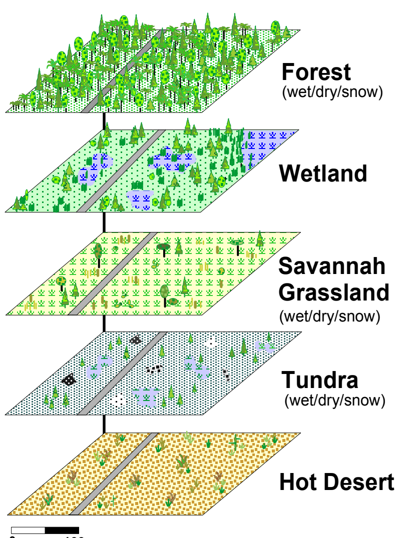


Figure 4: Thermal climate zones in the natural series.

The natural series consists of five thermal climate zones, ranging from "forest" to "hot desert" (Figure 4). Unlike the agricultural series, the natural series represents landscapes not greatly disturbed by cultural activity. Their names therefore correspond with biomes. Cold desert is excluded from the natural series because urban areas rarely exist in this environment. Water bodies are also excluded because the classification system is deliberately "land-based" in its representation of UHI measurement sites (note that shoreline environments are included in the "mixed" series). References to "rural" sites in UHI literature often confound agricultural and natural landscapes. Although the micro-scale surface climates of the two series may overlap, they differ fundamentally on the principle of landscape disturbance. The natural zones are characteristically abundant in vegetation and soils, with few if any built structures in the landscape. Sky view factor, aerodynamic roughness, soil thermal admittance, and albedo vary greatly across the natural series. Several of the zones are further divided by wet, dry, and snow-cover cases.

The mixed series comprises just two zones: "dispersed settlement" and "shore" (Figure 5). The former represents a transitional landscape of city and country, and the latter, land and water. By methodological convention, UHI measurement sites on the periphery of cities or near shorelines are often described as (crudely) "urban" or "rural." The mixed series is therefore intended to give better representation to transitional spaces that are frequently sampled by UHI investigators but poorly portrayed in the literature.

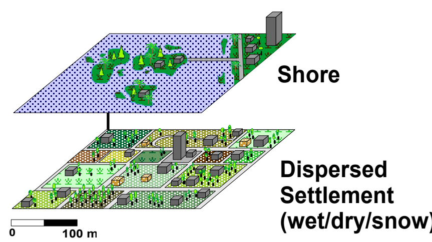


Figure 5: Thermal climate zones in the mixed series.

The twenty thermal climate zones are individually described and illustrated in standardized data sheets (for samples see Figure 6 and Figure 7). The data sheets are designed for quick and easy reference, helping users of the system to allocate field sites to appropriate classes with accuracy, objectivity, and minimal labor. Each data sheet includes a zone definition, computer sketches, photographs, and surface thermal properties.

5. CONCLUSION

Herewith we offer a prototype system of "thermal climate zones" for classifying UHI measurement sites at the local scale and in the canopy layer. UHI observations are ultimately measured and reported more objectively through standardized "inter-zone" temperature differences than through arbitrary "urban-rural" differences. "Thermal climate zones" are simple in design and easy to use. The zones provide an important educational and communications medium for heat island investigators worldwide; more fundamentally, they provide the building blocks of a new conceptual framework for re-defining UHI magnitude. Future development of this framework will involve computer modeling techniques to assess zone "thermal

SERIES: City	ZONE: *Blocks*	CODE: TCZ-5

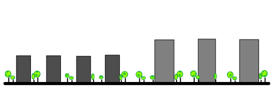
DEFINITION: Flat building profile; "boxy," high-rise structures, 3 to 10s of stories tall. Buildings uniform in design (height, width, materials); free-standing or attached in evenly spaced rows. Abundance of trees and open space between buildings. Sky view from among buildings is reduced. Heavy construction materials, primarily concrete, brick, or stone. Thick roofs and walls; roofs usually flat. Streets paved (asphalt, concrete), often geometric in layout. Moderate space heating/cooling demand. Moderate traffic density.

PROBABLE FUNCTION: Medium/high-density residential (apartment blocks, tower blocks, high-rise housing estates, tenements, terraced or row housing); commercial (hotels).

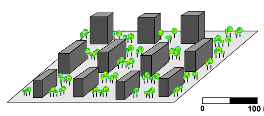
ANTICIPATED LOCATION: Densely populated cities. Modern suburban tracts or "new towns." Socialist-style cities ("block of flats"). Hotel/resort districts.

COMPUTER SKETCH

Side View



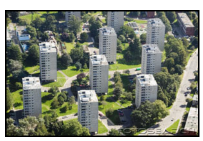
Oblique View



PHOTOGRAPHS

Eye Level

High Angle



ZONE PROPERTIES

SVF	% imp	DRC	albedo	μ	Q_F
0.70 – 0.90	60 – 80	6	0.12 – 0.20	1200 – 1500	20 – 35

KEY: SVF = sky view factor; % imp = fractional impervious coverage; DRC = Davenport roughness class; μ = surface thermal admittance ($Jm^{-2}s^{1/2}K^{-1}$); Q_F = mean annual anthropogenic heat flux (W/m^2).

Figure 6: Sample data sheet for "blocks."

SERIES: Agricultural	ZONE: *Flooded Fields*	CODE: TCZ-12

DEFINITION: Open, interlocking fields of paddy rice or flooded farmland. Plants and soils submerged in shallow water, generally covering more than 50 percent of the zone. Fields demarcated by well-developed infrastructure of dikes, ditches, waterways, roads. Open sky view; few dwellings, trees. Light traffic flow.

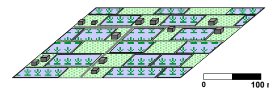
PROBABLE FUNCTION: Wet-cultivation (i.e., flooding, ponding) of rice and other semi-aquatic crops (e.g., watercress, cranberries); flooded cropland.

ANTICIPATED LOCATION: Universal.

COMPUTER SKETCH

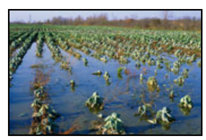
Side View

Oblique View



PHOTOGRAPHS

Eye Level



High Angle

ZONE PROPERTIES

SVF	% imp	DRC	albedo	μ	Q_F
> 0.95	< 10	4	0.08 – 0.12	2000 – 2500	0

NOTE: Paddy fields are flooded seasonally (rain-fed or irrigated). TCZ-13 is for flooded fields only; cropped or bare fields use TCZ-14, TCZ-15.

Figure 7: Sample data sheet for "flooded fields."

responsiveness" to diurnal heating and cooling cycles (Krayenhoff *et al*., 2009).

In closing, we acknowledge that no simple classification system can cover all landscapes. Our system is therefore balanced on simplicity and inclusiveness, and we believe this balance to contain the essence of a universally applicable system. Readers of this paper who sense apparent oversights or gaps in the system's representation of UHI landscapes, particularly in less-developed regions of the world, are invited to communicate those thoughts with us.

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