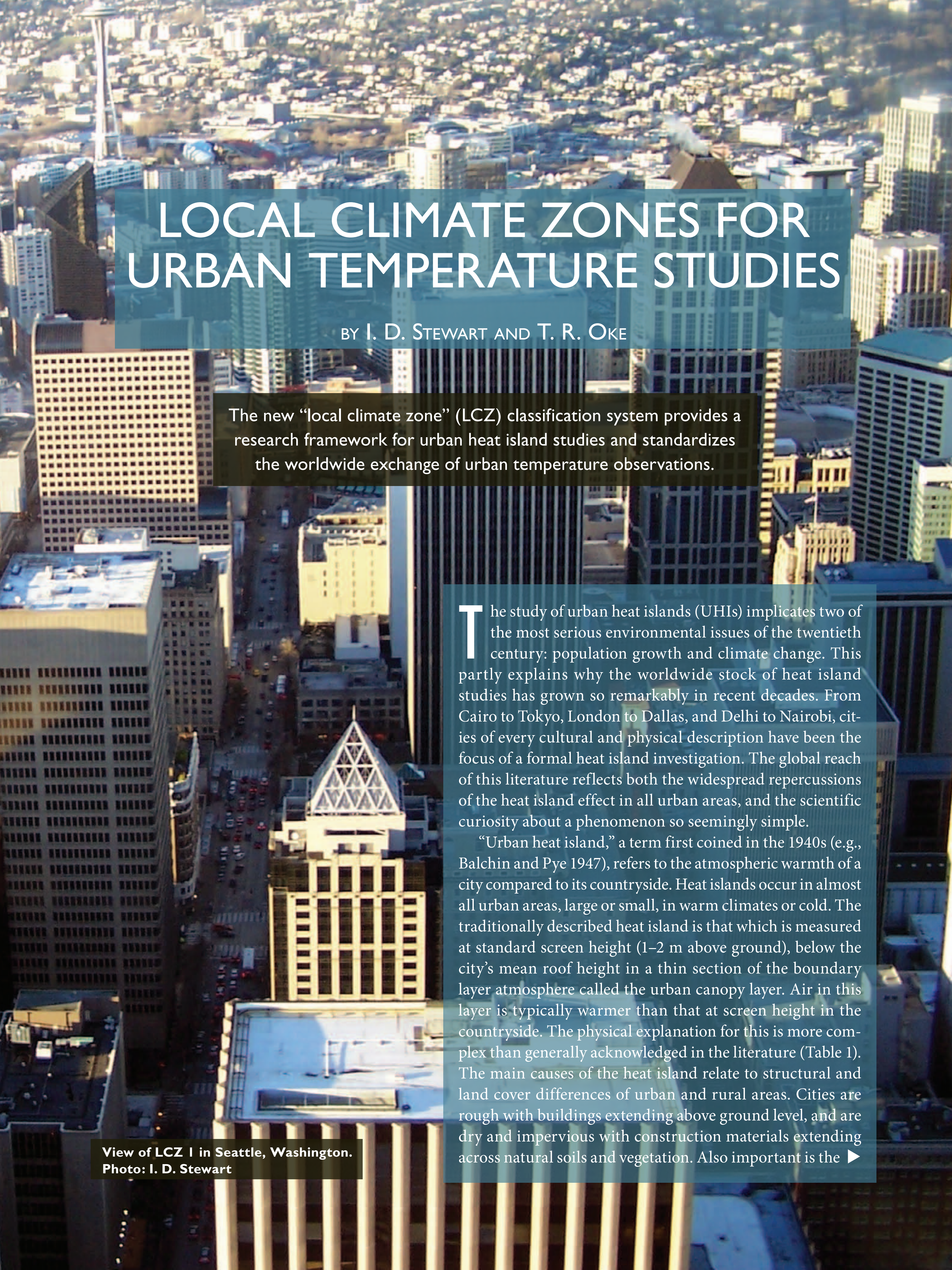
LOCAL CLIMATE ZONES FOR URBAN TEMPERATURE STUDIES

BY I. D. STEWART AND T. R. OKE

The new "local climate zone" (LCZ) classification system provides a research framework for urban heat island studies and standardizes the worldwide exchange of urban temperature observations.

The study of urban heat islands (UHIs) implicates two of the most serious environmental issues of the twentieth century: population growth and climate change. This partly explains why the worldwide stock of heat island studies has grown so remarkably in recent decades. From Cairo to Tokyo, London to Dallas, and Delhi to Nairobi, cities of every cultural and physical description have been the focus of a formal heat island investigation. The global reach of this literature reflects both the widespread repercussions of the heat island effect in all urban areas, and the scientific curiosity about a phenomenon so seemingly simple.

"Urban heat island," a term first coined in the 1940s (e.g., Balchin and Pye 1947), refers to the atmospheric warmth of a city compared to its countryside. Heat islands occur in almost all urban areas, large or small, in warm climates or cold. The traditionally described heat island is that which is measured at standard screen height (1–2 m above ground), below the city's mean roof height in a thin section of the boundary layer atmosphere called the urban canopy layer. Air in this layer is typically warmer than that at screen height in the countryside. The physical explanation for this is more complex than generally acknowledged in the literature (Table 1). The main causes of the heat island relate to structural and land cover differences of urban and rural areas. Cities are rough with buildings extending above ground level, and are dry and impervious with construction materials extending across natural soils and vegetation. Also important is the ▶



View of LCZ 1 in Seattle, Washington. Photo: I. D. Stewart

heat and moisture release from people and their activities. These urban characteristics alter the natural surface energy and radiation balances such that cities are relatively warm places (Oke 1982; Lowry and Lowry 2001).

The extra warmth in cities has several practical implications. Whether these are considered to be positive or negative depends upon the macroclimate of the city. In cities with a relatively cold climate, or with a cold season, the heat island can convey benefits such as cheaper house heating costs, improved outdoor comfort, fewer road weather hazards such as surface icing or fog, and more benign conditions for plant growth and animal habitat. On the other hand, heat islands in relatively hot climates or seasons can increase discomfort and potentially raise the threat of heat stress and mortality, and heighten the cost of air conditioning and the demand for energy.

Heat islands also have climatological implications. The fact that temperatures are elevated at urban stations means that their use in databases to assess historical climate series may have "contaminated" the global air temperature record. The concern is whether the presence of urban data has created a warm bias in the time series. Bias could occur if urban stations are used in the temperature record in greater numbers than is warranted by their representation as a land cover type on Earth.

To fully understand these and other issues, it has been the preoccupation of researchers for many decades to measure the heat island effect through simple comparisons of "urban" and "rural" air temperatures. The conventional approach is to gather temperatures at screen height for two or more fixed sites and/or from mobile temperature surveys. Sites are classified as either urban or rural, and their temperature differences are taken to indicate the heat island magnitude. Classifying measurement sites into urban and rural categories has given researchers a simple framework to separate the effects of city and country on local climate (e.g., Lowry 1977).

However, recent research shows that through this popular use of urban–rural classification, the methods and communication in heat island literature have suffered critically. In a review of many such studies, Stewart (2011a,b) found that more than three-quarters of the observational heat island literature fails to give quantitative metadata of site exposure or land cover. Most investigators simply rely on the so-called urban and rural qualifiers to describe the local landscapes of their measurement sites. Here we develop a climate-based classification of urban and rural sites that applies universally and relatively easily to local temperature studies using screen-level observations. Our aim in this classification is twofold: 1) to facilitate consistent documentation of site metadata and thereby improve the basis of intersite comparisons, and 2) to provide an objective protocol for measuring the magnitude of the urban heat island effect in any city. We do not aim to supplant the terms *urban* and *rural* from heat island discourse, but instead to encourage a more constrained use of these terms when describing the local physical conditions of a field site. The terms *urban* and *rural* alone cannot sufficiently describe a field site or its local surroundings.

INADEQUACIES OF SIMPLE URBAN–RURAL DIVISION.

Urban is defined in standard dictionaries as "constituting, forming, or including a city, town…or part of such," with *town* being a "densely populated area…opposed to the country or suburbs," and characterized physically as a "cluster of dwellings or buildings." *Rural*, in contrast, is an "agricultural or pastoral area . . . characteristic of the country or country life," with *country* being "the parts of a region distant from cities." From these definitions, we interpret rural landscapes to be less populated than cities, with fewer built structures and more abundant natural space for agricultural use, whereas urban landscapes have significantly more built structures and larger populations. By extension, suburban landscapes are those lying immediately outside or adjacent to a town or city, and that have natural and built-up spaces with population densities lower than cities but higher than the country.

While such definitions of *urban* and *rural* may be evocative of the landscape, they are vague as objects of scientific analysis (Stewart and Oke 2006). In the heat island literature, for example, the term *urban* evokes an eclectic mix of local settings from which its observations have originated: the wooden quarters

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Table 1. Causes of the urban heat island effect. Each cause represents an urban modification to the surface energy and radiation balance.

1. Greater absorption of solar radiation due to multiple reflection and radiation trapping by building walls and vertical surfaces in the city. Greater absorption is not, as often assumed, due solely to lower albedo of urban materials.
2. Greater retention of infrared radiation in street canyons due to restricted view of the radiatively "cold" sky hemisphere. Sky view becomes increasingly restricted with taller and more compact buildings.
3. Greater uptake and delayed release of heat by buildings and paved surfaces in the city. Often incorrectly attributed only to the thermal properties of the materials, this effect is also due to the solar and infrared radiation "trap" and to reduced convective losses in the canopy layer where airflow is retarded.
4. Greater portion of absorbed solar radiation at the surface is converted to sensible rather than latent heat forms. This effect is due to the replacement of moist soils and plants with paved and waterproofed surfaces, and a resultant decline in surface evaporation.
5. Greater release of sensible and latent heat from the combustion of fuels for urban transport, industrial processing, and domestic space heating/cooling. Heat and moisture are also released from human metabolism, but this is usually a minor component of the surface energy balance.

Source: Oke 1982

of old Hiroshima, Japan (Shitara 1957); the parks and playing fields of Pretoria, South Africa (Louw and Meyer 1965); the courtyards and stonework streets of London, England (Chandler 1965); the skyscraper canyons of Dallas, Texas (Ludwig 1970); the industrial plants and refineries of Ashdod, Israel (Sharon and Koplowitz 1972); the shaded avenues and lawns of New Delhi, India (Bahl and Padmanabhamurty 1979); the school and college grounds of Nairobi, Kenya (Okoola 1980); the factories and workshops of Cairo, Egypt (Robaa 2003); the brick and tin shanties of Sao Paulo, Brazil (Nunes da Silva and Ribeiro 2006); and the high-rise housing estates of Singapore (Chow and Roth 2006). A significant problem in this literature, and in heat island methodology, is that the term *urban* has no single, objective meaning, and thus no climatological relevance. What is described as urban in one city or region differs from that of another city (Fig. 1). The term *urban* is therefore impossible to define universally for its physical structure, its surface properties, or its thermal climate.

Equally problematic is that *urban* and *rural* are becoming outmoded constructs in landscape classification, for the developing world and especially Asia (Lin 1994; McGee and Robinson 1995; Lo and Yeung 1998). In these and other densely populated regions, the social, political, and economic space that separates cities and countrysides is no longer distinguished by a clear urban–rural divide. Urban form is becoming increasingly dispersed and decentralized as traditional and nontraditional land uses coexist, and as people, capital, commodities, and information flow continuously between city and countryside. Urban theorists now contend that the spatial demarcation between urban and rural is artificial, and that the relation between city and country is more accurately described as a continuum, or a dynamic, rather than as a dichotomy (Gugler 1996).

The densely populated Kanto Plain surrounding Tokyo is a perfect case in point. In a study of the Tokyo heat island, Yamashita (1990) paired an urban site in the city center with a rural site 60 km to the north. He defined UHI magnitude for Tokyo as the temperature difference between the urban and rural sites. Despite being located 60 km from the city center, the so-called rural site was still within the mixed urban–rural surroundings of metropolitan Tokyo, in the small city of Kumagaya. This gave a curious portrayal of the rural landscape to some urban climatologists (Fig. 2), but one that is, nonetheless, understandable given the dense settlement patterns of the Kanto Plain. Yamashita's remark that "the whole area of the Kanto Plain is more or less urbanized" correctly speaks to the difficulty of classifying urban and rural landscapes in highly dispersed and decentralized cities.

EXISTING URBAN AND RURAL LANDSCAPE CLASSIFICATIONS.

We recognize that all classifications are limited in scope and function, and further that none of the systems we review in this section was designed to classify heat island field sites, and none makes that claim. Therefore what we identify as advantageous, or restrictive, with these systems relates only to the aims of the new classification.

Chandler (1965) was perhaps the first heat island investigator to develop a climate-based classification of the city. He divided Greater London into four local regions, each distinguished by its climate, physiography, and built form. Following Chandler's lead, Auer (1978) proposed an urban–

rural classification for the city of St. Louis, Missouri. He recognized 12 "meteorologically significant" land uses in St. Louis, based on the city's vegetation and building characteristics. Ellefsen (1991) derived a system of 17 neighborhood-scale "urban terrain zones" (UTZs) from the geometry, street configuration, and construction materials of 10 U.S. cities. His was the first system to represent city structure and materials, initially for acid rain studies. A key feature of Ellefsen's system is the division of building types into "attached" and "detached" forms.

Fig. 1. Examples of urban field sites in climate literature. Conventional methodology defines these sites as universally "urban" despite obvious differences in building structure, land cover, and human activity: (a) modern core of Vancouver, Canada; (b) old core of Uppsala, Sweden; (c) town center of Toyono, Japan; (d) business district of Akure, Nigeria; (e) city airport of Phoenix, Arizona; (f) university campus of Szeged, Hungary.

Combining features of both Auer's and Ellefsen's schemes, Oke (2004, 2008) designed a simple and generic classification of city zones to improve siting of meteorological instruments in urban areas. His scheme divides city terrain into seven homogenous regions called "urban climate zones" (UCZs), which range from semi-rural to intensely developed sites. The zones are distinguished by their urban structure (building/street dimensions), cover (permeability), fabric (materials), metabolism (human activity), and potential to modify the natural, or "preurban," surface climate. Most recently, Loridan and Grimmond (2011) developed "urban zones for characterizing energy partitioning," or UZEs. Their classes are defined by threshold values for the active vegetative and built surface fractions of cities ("active" here meaning engaged in energy exchange). The classification helps atmospheric modelers to distinguish urban areas with respect to their partitioning of incoming radiation.

National land cover and land use classifications often include categories for both urban and rural environments. For example, the U.S. National Land Cover Dataset (NLCD) divides the coterminous United States into 16 land cover classes, 4 of which are deemed "urban oriented" (Homer et al. 2007). In some European countries, the "climatope" system has traditionally been used to classify urban terrain and urban climates, largely for planning purposes (Wilmers 1991; Scherer et al. 1999). Climatopes derive from local knowledge of wind, temperature, land use, building structure, surface relief, and population density. These data are integrated across an urban area to reveal special climates of local places, or climatopes. Wilmers (1991) identified nine such climates for the city of Hannover, Germany, based on vegetation, surface structure, and land use criteria. Scherer et al. (1999) documented many more climatopes in Basel, Switzerland, based on ventilation and land cover characteristics.

These previous classifications contain many features that align with the aims of heat island observation. Their limitations, however, must be recognized. First, not all classifications use a full set of surface climate properties to define its classes. A complete set consists of the physical properties of surface structure, cover, fabric, and metabolism (Oke 2004). Second, a system that excludes rural landscapes is not well suited to heat island investigation, nor is one with class names and definitions that are culture or region specific. The classifications of Chandler, Auer, Ellefsen, and Oke are all predisposed to the form and function of modern, developed cities, so their use in more diverse economic settings is limited. Third, although the climatope concept is well adapted to most urban settings, its class names and definitions vary widely with place, and thus cannot provide classification systems with a means for comparison.

Fig. 2. "Rural" site used by Yamashita (1990) to measure UHI magnitude in Tokyo (red circles indicate site location). Urban and rural influences on surface climate are seen at (top, center) micro and (center, bottom) local scales. This overlap in landscapes and spatial scales on the Kanto Plain makes the urban–rural dichotomy an awkward fit for site classification. Aerial photographs courtesy of Google Earth.

CONSTRUCTING A NEW CLASSIFICATION SYSTEM.

In a classic paper on the logic, method, and theory of classification, Grigg (1965) listed several criteria that a system should meet. First, it should invoke a simple and logical nomenclature by which objects/areas can be named and described. A system's nomenclature is critical to its validity and acceptance. Second, a classification system should facilitate information transfer by associating objects/areas in the real world with an organized system of generic classes. Users can then make comparative statements about the members belonging to each class. This condition led Grigg to his third and most important criterion: inductive generalization. A properly constructed classification system should simplify the objects/areas under study, and thereafter promote theoretical statements about their properties and relations. To Grigg's criteria, we add that a new classification of urban and rural field sites should be inclusive of all regions, independent of all cultures, and, for heat island assessment, quantifiable according to class properties that are relevant to surface thermal climate at the local scale (i.e., hundreds of meters to several kilometers).

Classification by logical division. Scientific classification is essentially a process of definition. It begins with a "universe" class, which is divided into subclasses (Black 1952). The basis for division at each class level is a differentiating principle, or property, of theoretical interest. The universe for the new classification is "landscape," which we define as a local-scale tract of land with physical and/or cultural characteristics that have been shaped by physical and/or cultural agents. The landscape universe is divided according to properties that influence screen-height temperature, namely surface structure (height and spacing of buildings and trees) and surface cover (pervious or impervious). *Surface structure* affects local climate through its modification of airflow, atmospheric heat transport, and shortwave and longwave radiation balances, while *surface cover* modifies the albedo, moisture availability, and heating/cooling potential of the ground. These properties tend to "cluster" spatially, such that in locations where the building height-to-width ratio is large, so is the fraction of impervious cover and the density of urban construction materials.

Dividing the landscape into these properties generates dozens of prototype classes, many having clusters that are considered highly improbable or logically unacceptable in the real world (e.g., closely spaced buildings on pervious cover or closely spaced trees on impervious cover). Such clusters were removed from the system while others were added to represent landscapes defined not by their structural or surface cover characteristics, but by building materials or anthropogenic heat emissions. The resulting classes were quantified by their surface properties and assigned simple, concise names. Throughout this process, prospective users of the system in the international climate community were asked for feedback on the general nature of the system, its application to local settings, and its cultural and regional biases. This early exposure of the system to its target community resulted in substantial changes to the number, nature, and naming of the individual classes.

Data sources. Quantitative data to characterize the classes by their surface properties were selected from the urban climate observational and numerical modeling literature. Measured and estimated values of geometric, thermal, radiative, metabolic, and surface cover properties were gathered from urban and rural field sites worldwide. Quantitative data were also retrieved from the classifications of Anderson et al. (1976), Auer (1978), Häubi and Roth (1980), Ellefsen (1990/91), Theurer (1999), and Oke (2004), and from reviews of empirical urban climate literature (e.g., Wieringa 1993; Grimmond and Oke 1999).

Data to adapt the classes to the real world were chosen from the urban design literature, which gives *qualitative* attributes to urban form through expressions of "fabric," "texture," and "morphology" (e.g., Brunn and Williams 1983; O'Connor 1983; Vance 1990; Kostof 1991; Potter and Lloyd-Evans 1998). These are the same expressions to which urban climatologists give *quantitative* attributes. This overlap was especially useful to assimilate regional urban form into the classification system, and to balance its temporal (old vs modern) and spatial (core vs periphery) representation. These data also give support to culturally neutral definitions for each class.

LOCAL CLIMATE ZONES.

Hereafter, all classes to emerge from logical division of the landscape universe are called "local climate zones" (LCZs; Table 2) (Stewart 2011a). The name is appropriate because the classes are *local* in scale, *climatic* in nature, and *zonal* in representation. We formally define local climate zones as regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale. Each LCZ has a characteristic screen-height temperature regime that is most apparent over dry surfaces, on calm, clear nights, and in areas of simple relief. These temperature regimes persist

Table 2. Abridged definitions for local climate zones (see electronic supplement for photographs, surface property values, and full definitions). LCZs 1–9 correspond to Oke's (2004) urban climate zones.

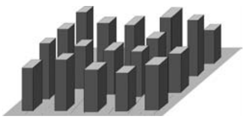
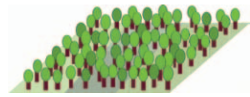
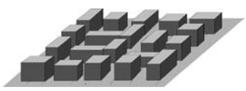
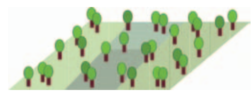
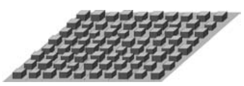
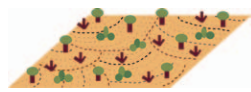
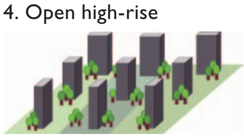
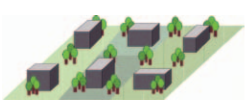
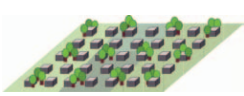
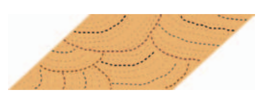
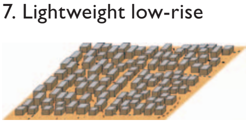
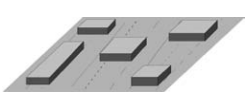
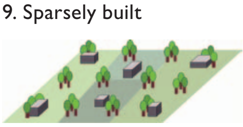
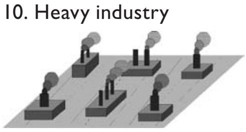
Built types	Definition	Land cover types	Definition
1. Compact high-rise 	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees 	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise 	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees 	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise 	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub 	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise 	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants 	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise 	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved 	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise 	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand 	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise 	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water 	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise 	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	**VARIABLE LAND COVER PROPERTIES** Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.	
9. Sparsely built 	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	*b. bare trees* *s. snow cover*	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo. Snow cover >10 cm in depth. Low admittance. High albedo.
10. Heavy industry 	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.	*d. dry ground* *w. wet ground*	Parched soil. Low admittance. Large Bowen ratio. Increased albedo. Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Table 3. Values of geometric and surface cover properties for local climate zones. All properties are unitless except height of roughness elements (m).

Local climate zone (LCZ)	Sky view factor[a]	Aspect ratio[b]	Building surface fraction[c]	Impervious surface fraction[d]	Pervious surface fraction[e]	Height of roughness elements[f]	Terrain roughness class[g]
LCZ 1 *Compact high-rise*	0.2–0.4	> 2	40–60	40–60	< 10	> 25	8
LCZ 2 *Compact midrise*	0.3–0.6	0.75–2	40–70	30–50	< 20	10–25	6–7
LCZ 3 *Compact low-rise*	0.2–0.6	0.75–1.5	40–70	20–50	< 30	3–10	6
LCZ 4 *Open high-rise*	0.5–0.7	0.75–1.25	20–40	30–40	30–40	>25	7–8
LCZ 5 *Open midrise*	0.5–0.8	0.3–0.75	20–40	30–50	20–40	10–25	5–6
LCZ 6 *Open low-rise*	0.6–0.9	0.3–0.75	20–40	20–50	30–60	3–10	5–6
LCZ 7 *Lightweight low-rise*	0.2–0.5	1–2	60–90	< 20	<30	2–4	4–5
LCZ 8 *Large low-rise*	>0.7	0.1–0.3	30–50	40–50	<20	3–10	5
LCZ 9 *Sparsely built*	> 0.8	0.1–0.25	10–20	< 20	60–80	3–10	5–6
LCZ 10 *Heavy industry*	0.6–0.9	0.2–0.5	20–30	20–40	40–50	5–15	5–6
LCZ A *Dense trees*	<0.4	>1	<10	<10	>90	3–30	8
LCZ B *Scattered trees*	0.5–0.8	0.25–0.75	<10	<10	>90	3–15	5–6
LCZ C *Bush, scrub*	0.7–0.9	0.25–1.0	<10	<10	>90	<2	4–5
LCZ D *Low plants*	>0.9	<0.1	<10	<10	>90	<1	3–4
LCZ E *Bare rock or paved*	>0.9	<0.1	<10	>90	<10	<0.25	1–2
LCZ F *Bare soil or sand*	>0.9	<0.1	<10	<10	>90	< 0.25	1–2
LCZ G *Water*	>0.9	<0.1	<10	<10	>90	–	1

[a] Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere

[b] Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G)

[c] Ratio of building plan area to total plan area (%)

[d] Ratio of impervious plan area (paved, rock) to total plan area (%)

[e] Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)

[f] Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F) (m)

[g] Davenport et al.'s (2000) classification of effective terrain roughness (z_0) for city and country landscapes. See Table 5 for class descriptions

TABLE 4. Values of thermal, radiative, and metabolic properties for local climate zones. All values are representative of the local scale.

Local climate zone (LCZ)	Surface admittance[a]	Surface albedo[b]	Anthropogenic heat output[c]
LCZ 1 *Compact high-rise*	1,500–1,800	0.10–0.20	50–300
LCZ 2 *Compact midrise*	1,500–2,200	0.10–0.20	<75
LCZ 3 *Compact low-rise*	1,200–1,800	0.10–0.20	<75
LCZ 4 *Open high-rise*	1,400–1,800	0.12–0.25	<50
LCZ 5 *Open midrise*	1,400–2,000	0.12–0.25	<25
LCZ 6 *Open low-rise*	1,200–1,800	0.12–0.25	<25
LCZ 7 *Lightweight low-rise*	800–1,500	0.15–0.35	<35
LCZ 8 *Large low-rise*	1,200–1,800	0.15–0.25	<50
LCZ 9 *Sparsely built*	1,000–1,800	0.12–0.25	<10
LCZ 10 *Heavy industry*	1,000–2,500	0.12–0.20	>300
LCZ A *Dense trees*	unknown	0.10–0.20	0
LCZ B *Scattered trees*	1,000–1,800	0.15–0.25	0
LCZ C *Bush, scrub*	700–1,500	0.15–0.30	0
LCZ D *Low plants*	1,200–1,600	0.15–0.25	0
LCZ E *Bare rock or paved*	1,200–2,500	0.15–0.30	0
LCZ F *Bare soil or sand*	600–1,400	0.20–0.35	0
LCZ G *Water*	1,500	0.02–0.10	0

[a] Ability of surface to accept or release heat ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$). Varies with soil wetness and material density. Few estimates of local-scale admittance exist in the literature; values given here are therefore subjective and should be used cautiously. Note that the "surface" in LCZ A is undefined and its admittance unknown.

[b] Ratio of the amount of solar radiation reflected by a surface to the amount received by it. Varies with surface color, wetness, and roughness.

[c] Mean annual heat flux density ($W\ m^{-2}$) from fuel combustion and human activity (transportation, space cooling/heating, industrial processing, human metabolism). Varies significantly with latitude, season, and population density.

year-round and are associated with the homogeneous environments or ecosystems of cities (e.g., parks, commercial cores), natural biomes (e.g., forests, deserts), and agricultural lands (e.g., orchards, cropped fields). Each LCZ is individually named and ordered by one (or more) distinguishing surface property, which in most cases is the height/packing of roughness objects or the dominant land cover. The physical properties of all zones are measurable and nonspecific as to place or time (Tables 3 and 4).

The landscape universe consists of 17 standard LCZs, of which 15 are defined by surface structure and cover and 2 by construction materials and anthropogenic heat emissions. The standard set is divided into "built types" 1–10, and "land cover types" A–G (Table 2). Built types are composed of constructed features on a predominant land cover, which is *paved* for compact zones and *low plants / scattered trees* for open zones. Land cover types can be classified into seasonal or ephemeral properties (i.e., bare trees, snow-covered ground, dry/wet ground).

Thermal differentiation of LCZ classes. The logical structure of the LCZ system is supported by observational and numerical modeling data (Stewart and Oke 2010; Stewart 2011a). Mobile temperature observations from Uppsala, Sweden (Sundborg 1951; Taesler 1980); Nagano, Japan (Sakakibara and Matsui 2005); and Vancouver, Canada (T. Oke and A. Christen) were used to measure thermal contrasts among LCZ classes. During calm, clear evenings, thermal contrasts are driven

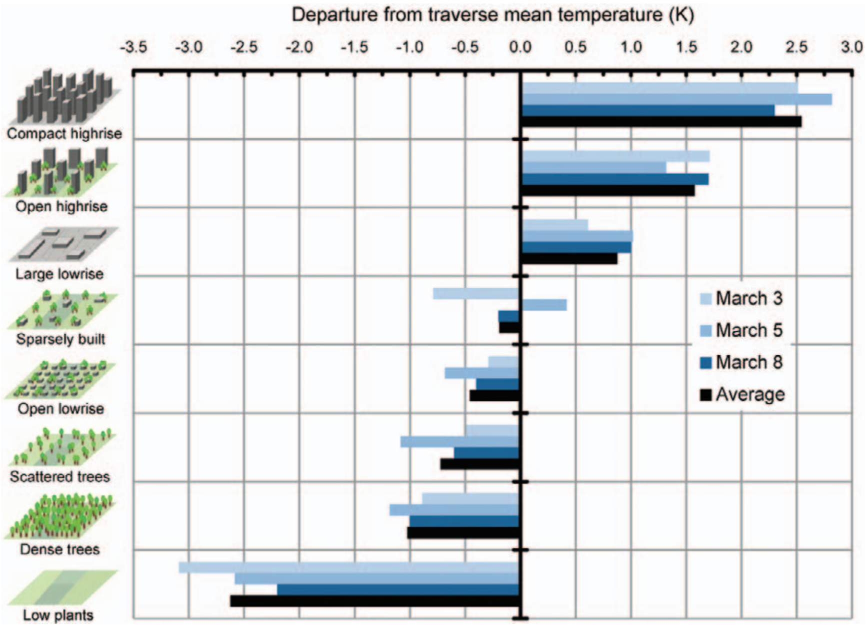


Fig. 3. Thermal differentiation of local climate zones using temperatures from automobile traverses in Vancouver during calm, clear evenings, Mar 2010. All measurements were made with an aspirated and insulated copper-constantan thermocouple (precision ±0.2 K) at 1.5 m above ground. Temperatures are adjusted to a standard base time of 2 h after sunset. Raw temperature data provided by Andreas Christen (University of British Columbia).

largely by building geometry and land cover (Fig. 3). Contrasts between classes with significant differences in geometry and cover can often exceed 5 K, whereas contrasts between classes with lesser physical difference can be less than 2 K. This pattern is easily disrupted by the dynamical and seasonal effects of surface wetness, relief, tree cover, snow cover, and anthropogenic heat, all of which can override or offset the unvarying effects of building form and surface cover. Numerical surface and atmospheric models show that the diurnal temperature range in each class decreases with increasing impervious surface fraction and height/density of buildings (Fig. 4). These simulations follow the approach of Krayenhoff et al. (2009) in an attempt to aid the assessment of LCZ thermal responsiveness. Computer modeling of canopy layer climates is not sufficiently developed to enable more accurate predictions of thermal microclimates at screen level for individual urban sites.

The extent to which LCZs reveal characteristic regimes for other meteorological variables in the urban canopy layer, such as wind and humidity, has yet to be explored. Atmospheric properties that blend at the top of the roughness sublayer (typically more than twice the height of the canopy layer) will not classify discretely into LCZs. This is true of surface energy balance fluxes in the urban boundary layer. Urban energy balance zones (e.g., UZEs; Loridan and Grimmond 2011) are therefore unlikely to coincide exactly with LCZs because similar flux densities can occur above canopy layers with distinctly different microscale structure, land cover, and thermal climate.

Communication. Definitions and physical properties of all LCZs are given in 17 illustrative datasheets [see the appendix for sample sheets 1, 6, and D; see electronic supplement online at http://dx.doi.org/10.1175/BAMS-D-11-00019.2 for full set]. Using these sheets, urban climate investigators can classify landscapes and field sites with consistency and efficiency, and link standardized site metadata to all temperature observations. These metadata include photographs of LCZs in different regional settings and bar charts of zone properties relating to surface structure (sky view factor, aspect ratio, roughness element height), surface cover (plan fraction occupied by buildings, vegetation, and impervious ground), surface fabric (thermal admittance, surface albedo), and human activity (anthropogenic heat output). For definitions of these properties, refer to Tables 3 and 4, and to the datasheet key in the appendix.

GUIDELINES FOR USING THE LCZ CLASSIFICATION SYSTEM. The LCZ system is inherently generic and cannot capture the peculiarities of every urban and rural site. Its view of the landscape universe is highly reductionist, and, like all classifications, its descriptive and explanatory powers are limited. LCZs represent a simple composition of buildings, roads, plants, soils, rock, and water, each in varying amounts and each arranged uniformly into 17 recognizable patterns. The internal homogeneity portrayed by each LCZ is unlikely to be found in the real world, except in planned or intensely managed settings (e.g., city parks, new housing estates). The 17 patterns should nevertheless be familiar to users in most cities, and should be adaptable to the local character of most sites.

The LCZ classes are each physically discrete in surface structure and land cover, such that the boundaries separating most classes can be delineated on a city map or aerial photograph. However, the thermal climate across those boundaries is spatially continuous—the screen-level air temperature of one zone blends gradually into that of its neighboring zones. This effect arises from advection of heat and moisture across areas of different surface structure, land cover, and human activity. As air crosses the border between neighboring zones, it gradually adjusts to a new set of internal boundary conditions, forming thermal transitions—not sudden breaks at zone borders. The upwind fetch required for air at screen height to become fully adjusted to its underlying surface is typically 200–500 m, depending on surface roughness, building geometry, and atmospheric stability conditions (Oke 1987; Wieringa 1993). Each LCZ should therefore have a minimum diameter of 400–1,000 m (i.e., a radius of 200–500 m) so that the adjusted portion of its internal boundary layer lies entirely within the zone and does not overlap with surrounding LCZs of different structure or cover. If the minimum diameter for an LCZ is met, it remains possible for air aloft—the properties of which have been modified by the surfaces of an upwind LCZ—to be entrained down into the surface layer of a leeward zone.

Three-step process. Users should observe the following steps when classifying field sites into LCZs, whether for a multiyear climate study or a short-term field survey. The temporal scope of a study dictates when, or if, the seasonal or ephemeral properties of the sites need to be classified (e.g., soil moisture, snow cover, tree leaf cover). Classification of sites into LCZs draws substantively from Aguilar et al. (2003) and Oke (2004, 2008), whose recommendations for siting instruments and collecting metadata apply to nonurban and urban settings, respectively. Their recommendations [adopted by the World Meteorological Organization (WMO)], together with those included here, lead to consistent use of the LCZ system. Furthermore, they require only minimal site metadata and surface characterization, and they avert potential pitfalls that might compromise the classification of a site. [For regional examples of LCZ classification, see Stewart and Oke (2009).]

Step 1: Collect site metadata. Users must collect appropriate site metadata to quantify the surface properties of the source area (as defined in step 2) for a temperature sensor. This is best done by a visit to the field sites in person to survey and assess the local horizon, building geometry, land cover, surface wetness, surface relief, traffic flow, and population density [see sample template in Oke (2004)]. If a field visit is not possible, secondary sources of site metadata include aerial photographs, land cover/land use maps, satellite images (e.g., Google Earth), and published tables of property values (e.g., Davenport

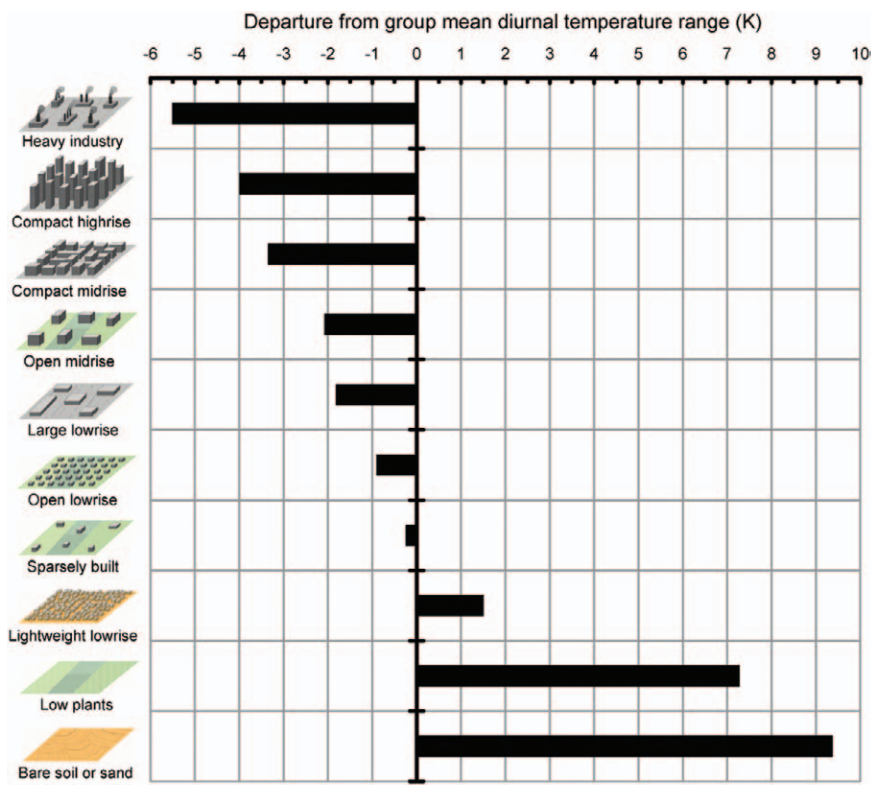


Fig. 4. Simulated values for diurnal temperature range in select local climate zones. Temperature values are representative of the surface-layer air. All zones except *low plant cover* and *bare soil or sand* were modeled with an updated version of the Town Energy Balance scheme (Masson 2000). *Low plant cover* and *bare soil or sand* were modeled with the Coupled Atmosphere–Plant–Soil scheme (Mahrt and Pan 1984).

terrain roughness lengths; see Table 5). These data are usually available at little or no cost to the user.

It is important that LCZ users quantify the *local-scale* character of their sites: anomalous microscale features of land cover, building geometry, and human activity must not distract an assessment of the broader surroundings. However, if the area of influence for a field site is too heterogeneous to derive locally representative values from its surface properties, users are advised to designate the site "unclassified" and to find a more homogeneous setting for observation.

Step 2: Define the thermal source area. The thermal source area for a temperature measurement is the total surface area "seen" by the sensor (sometimes called its "footprint" or "circle of influence"). In other words, it is the surface area from which the temperature signal is derived and subsequently is carried, via turbulent transport, to the sensor. The source area of standard contact thermometers extends upwind for meters to kilometers depending on instrument height, surface geometry, and boundary layer wind and stability conditions (Kljun et al. 2002).

The size, shape, and orientation of turbulent source areas evolve with time (Fig. 5). Over periods of, say, an hour, the area is elliptical and oriented in the upwind direction of the sensor (Schmid 2002). Because of temporal changes in stability, and especially wind direction, the ellipses are centered upon, but oscillate around, the measurement site so that, over time, they form a misshapen circle. The dimensions of the source area should be computed, ideally with a footprint model (e.g., Kljun et al. 2002; Schmid 2002). The approximate size and orientation of the area can otherwise be estimated from (a) the vectors of a wind rose for that location and time period, and (b) an empirically based "rule of thumb" that states the source area for a screen-height temperature sensor in a neutrally stable atmosphere extends, on average, no more than a few hundred meters away (Tanner 1963; Mizuno et al. 1991; Runnalls and Oke 2006).

Estimating the source area for a screen-height thermometer in an urban area is a challenging task that has hardly been scientifically investigated. It can be anticipated that screen-height temperature measurements in a canopy layer with compact buildings have smaller and more poorly defined source areas than those of open urban and rural zones. The sources will include upwind buildings, the walls and floor of an upwind street, and perhaps a branching network of more distant street canyons that channel surface air toward the measurement site.

Table 5. Davenport classification of effective terrain roughness. Correspondence with LCZs is given for each Davenport class.

Davenport class	Roughness length, z_0 (m)	Landscape description	LCZ correspondence
1. Sea	0.0002	Open water, snow-covered flat plain, featureless desert, tarmac, and concrete, with a free fetch of several kilometers.	E, F, G
2. Smooth	0.005	Featureless landscape with no obstacles and little if any vegetation (e.g., marsh, snow-covered or fallow open country).	E, F
3. Open	0.03	Level country with low vegetation and isolated obstacles separated by 50 obstacle heights (e.g., grass, tundra, airport runway).	D
4. Roughly open	0.10	Low crops or plant covers; moderately open country with occasional obstacles (e.g., isolated trees, low buildings) separated by 20 obstacle heights.	7, C, D
5. Rough	0.25	High crops, or crops of varying height; scattered obstacles separated by 8 to 15 obstacle heights, depending on porosity (e.g., buildings, tree belts).	5–10, B, C
6. Very rough	0.5	Intensely cultivated landscape with large farms and forest clumps separated by 8 obstacle heights; bushland, orchards. Urban areas with low buildings interspaced by 3 to 7 building heights; no high trees.	2, 3, 5, 6, 9, 10, B
7. Skimming	1.0	Landscape covered with large, similar-height obstacles, separated by 1 obstacle height (e.g., mature forests). Dense urban areas without significant building-height variation.	2, 4
8. Chaotic	≥ 2	Landscape with irregularly distributed large obstacles (e.g., dense urban areas with mix of low and high-rise buildings, large forest with many clearings).	1, 4, A

Source: Davenport et al. (2000)

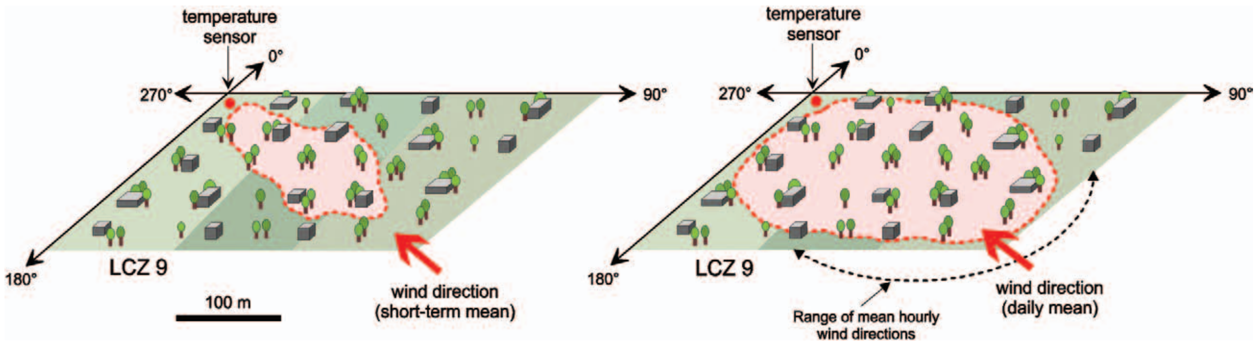


Fig. 5. Hypothetical source areas and surface wind directions for a screen-height temperature sensor in prevailing southeast winds. (left) Short-term (<1 h) source area. (right) Mean daily source area.

Quantifying the surface properties for field sites and source areas located on or near the border of two (or more) zones is problematic. If the location of the sensor can be moved, it should be placed where it samples from a single LCZ. Land cover and exposure at that location should then be representative of the designated LCZ: for compact built zones (e.g., LCZs 1–3), "representative" implies a sheltered street canyon with paved ground; for open built zones (e.g., LCZs 4–6), it implies an exposed setting with vegetated ground, scattered trees, and nearby buildings. If the location of the sensor cannot be moved, temperature data retrieved from that site should be stratified first according to wind direction, then to LCZ. In transitional urban–rural areas, or along breaks in land use, split classifications will occur. A site with split classification is less ideal for heat island studies because changes in airflow and stability conditions confuse the relation between surface form/cover and air temperature. It is recommended that transitional areas be avoided when siting meteorological instruments (Oke 2004, 2008).

Step 3: Select the local climate zone. Metadata collected in step 1 should lead users to the best, not necessarily exact, match of their field sites with LCZ classes. Metadata are unlikely to match perfectly with the surface property values of one LCZ class. If the measured or estimated values align poorly with those in the LCZ datasheets, the process of selecting a best-fit class becomes one of interpolation rather than straight matching. Users should first look to the surface cover fractions of the site to guide this process. If a suitable match still cannot be found, users should acknowledge this fact and highlight the main difference(s) between their site and its nearest equivalent LCZ. For example, a site having considerably more traffic flow (and therefore anthropogenic heat flux) or noticeably taller, shorter, or more variable building heights than its nearest LCZ class should be identified by these differences and described with the appropriate LCZ name.

Alternatively, users can create new subclasses for sites that deviate from the standard set of classes shown in Table 2. New subclasses represent combinations of built types, land cover types, and land cover properties (Fig. 6). The notation for new subclasses is LCZ X_{ai}, where X is the higher parent class in the standard set of LCZs, a is the lower parent class (if applicable) from the standard set, and i is a variable or ephemeral land cover property (if applicable). Land cover properties are selected from the subset of bare trees (*b*), snow cover (*s*), dry ground (*d*), and wet ground (*w*) (Table 2). Identifiers *a* and *i* may each be assigned one or more classes or properties. For example, a site whose building geometry is *open midrise* (LCZ 5) but whose surface cover is predominantly *bush, scrub* (LCZ C) should be notated as LCZ 5_C to represent the main features of its two parent classes, the first in a higher position of the LCZ order (baseline character 5) and the second in a lower position (subscript C). By this convention, other subclasses include *open midrise* with *paved ground* (LCZ 5_E), *open midrise* with *open low-rise* (LCZ 5_6), *open low-rise* with *dense, bare trees* (LCZ 6_{Ab}), *low plants* with *wet ground* (LCZ D_w), and *bare soil* with *dry ground* (LCZ F_d).

All standard LCZ classes with extensive pervious cover (A–D, F, 4–6, and 9) are prescribed an intermediate soil moisture status, meaning that soil water content is below field capacity but above wilting point. In this state, soil moisture is available to plants and the soil feels pliable and slightly sticky. If soils are saturated (i.e., water content is above field capacity, and water is easily squeezed from the soil), the site should be subclassified as "wet" (with subscript *w*). Soils submerged in shallow water due to natural drainage or flood irrigation (e.g., wetlands, paddy fields, detention storage ponds) are also considered wet. If soils are parched (i.e., water content is below wilting point), soil moisture is unavailable to plants and the soil feels loose, powdery, or hard-crusted. The site in this case should be subclassified as "dry" (subscript *d*). Finally, if a site is covered with >10 cm of snow, it should be subclassified as "snow cover" (subscript *s*).

Although subclasses add flexibility to the LCZ system, we give several caveats for their use. First, the system as proposed does not provide surface property values for subclasses, and thus their thermal climates may not be known a priori. At best, one can estimate the surface property values—and surface air temperatures—by weighting the known values of two (or more) standard classes. Second, the thermal climate of an LCZ subclass is not expected to differ significantly from either of its two (or more) parent classes, because maximum thermal contrasts between successive zones in the standard set are typically no more than 1–2 K (Stewart and Oke 2010). Third, the purpose of LCZs is to ease the process of site classification and metadata reporting for heat island investigators. Creating too many, or too complex, subclasses undermines this principal function. While subclasses may enhance the physical description of a site, they may not improve communication or comparison of that site with other studies. Subclasses are justified when they describe sites whose secondary features are thought to affect the local climate, or whose features may otherwise relate to the particular aims of a climate investigation.

Despite preference for using the standard set of 17 LCZs, we recognize that subclassification is unavoidable if the ground at a site is snow-covered or extremely dry/wet, or if the deciduous trees are bare. When classifying a site for a short-term study (e.g., days, weeks, or months), the LCZ notation should include variable land cover properties (i.e., subscripts *b*, *s*, *d*, and *w*), but only if the site differs from the prescribed definitions of the standard LCZ classes (Table 2). Most sites with extensive tree or pervious cover will experience significant change in land cover properties due to synoptic weather patterns (e.g., drought, monsoon), agricultural practices (e.g., planting, harvesting), or seasonal cycles (e.g., leaf growth/leaf drop). If, however, the sites are classified for long-term studies (e.g., years), subclassification

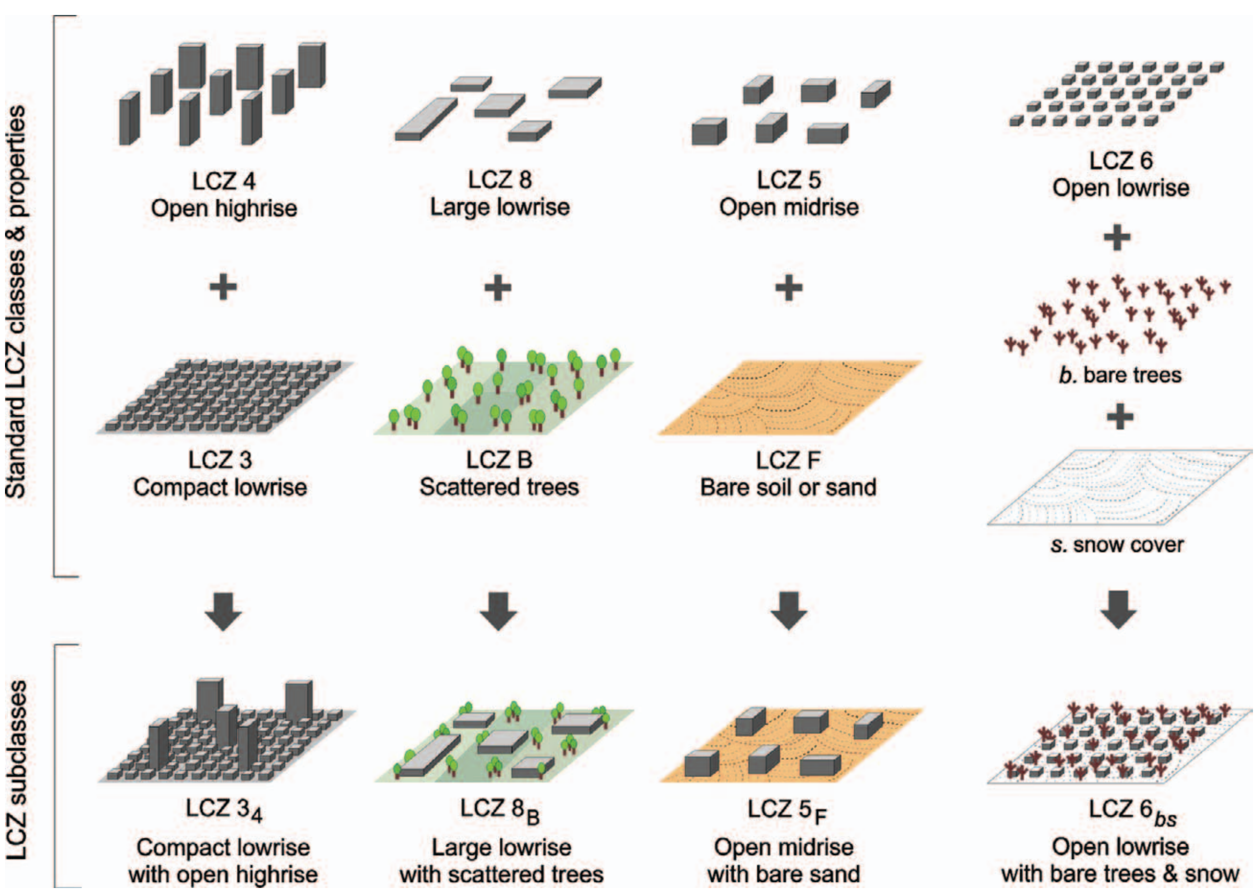


Fig. 6. LCZ subclasses to represent combinations of "built" and "land cover" types.

is unnecessary because seasonal and/or ephemeral change is either implicit in the name (as in classes with extensive tree or pervious cover) or irrelevant to the local climate (classes with no tree or pervious cover). Long-term temperature data from sites experiencing seasonal and/or ephemeral change should be stratified into time periods that correspond with different land cover properties, so that underlying trends in the temperatures can be found. A site covered by low plants year-round, the soils of which are saturated during a rainy season, will be notated as LCZ D_w if used in a short-term study during the wet period and as LCZ D if used in a long-term study of several seasons or years.

Updating zone designations. Correspondence between field sites and LCZ classes will vary with physical and cultural changes to the landscape. This is a virtual certainty in any active urban area as land clearance and development occur. Updating LCZ designations is crucial for all sites, particularly those used in long-term temperature studies. A changing site will "progress" or "regress" through the natural, built, compact, and open forms of the LCZ classification. This allowance for landscape change ensures that the LCZ system stays relevant through time. Sites located on the edges of cities where urban growth and environmental change are rapid, or in the cores of cities where land redevelopment and large-scale greening projects are taking place, should be surveyed and classified annually. For sites used in mobile or short-term stationary surveys, the frequency of updates is dictated largely by day-to-day variations in weather and soil moisture (e.g., rainfall, snow melt, irrigation).

APPLICATION OF LOCAL CLIMATE ZONES.

Defining UHI magnitude. The urban–rural temperature difference, or UHI magnitude, is the most widely cited measure of city climate modification in the environmental sciences. It is also the most poorly represented (Stewart 2011a; Stewart and Oke 2006). We therefore propose a new framework to extract UHI magnitudes from local temperature observations. With this new framework, UHI magnitude is an LCZ temperature difference (e.g., $\Delta T_{\mathrm{LCZ\ 1\ -\ LCZ\ D}}$), not an "urban–rural" difference (ΔT_{u-r}). LCZ differences are more conducive to analysis, and less prone to confusion, because they highlight the common surface and exposure characteristics of the compared field sites, and they invite physically based explanations of UHI magnitude. The former is especially true if the temperature measurements of a heat island investigation are strategically located to reduce the variable effects of surface relief, elevation, and water bodies on UHI magnitude. If such "control" is not possible—and thus the dynamical effects of local relief, elevation, and/or water bodies are at risk of being confused with the thermal effects of buildings and land cover—the sites should be described for more than just their LCZ designations. In this way, the LCZ system prompts investigators to recognize and separate urban from nonurban influences on temperature. [See Lowry (1977), Lowry and Lowry (2001), Oke (2004), and Stewart (2011b) for discussions of experimental design and heat island observation.]

Public scrutiny of heat island literature. The assessment of Stewart (2011b) that "poor scientific practice" has compromised nearly one-half of the published heat island literature should give pause. Several of the weaknesses contributing to that assessment can be improved upon with the new LCZ classification system. While using LCZs, heat island investigators must aim to move their studies to a higher level of inquiry by connecting observations and explanations with underlying energetics, or with other heat-related phenomena of the urban climate. Towards that goal, it is their responsibility to follow the relatively simple guidelines for instrument siting, exposure, metadata, and classification as stated in the present paper and in the WMO (2008) *Guide to Meteorological Instruments and Methods of Observation*. Reviewers and editors have a critical role to play in this movement: they must advocate and uphold a more responsible, ethical code for gathering and reporting heat island observations.

Climate modeling, weather forecasting, and historical temperature analysis. Parameterization of the urban canopy in numerical climate models and weather prediction schemes can be improved with LCZs and their surface morphological and land cover data. LCZs can provide input data for numerical climate models that incorporate urban canopy parameters into their formulations to forecast temperature, wind, precipitation, etc. Likewise, statistical regression models can use LCZ input data to predict intra-urban temperature patterns and UHI magnitudes.

In global climate change studies, the classification of weather stations and observatories into LCZ classes, rather than "urban" and "rural" classes, could lead to more accurate assessments of urban bias in the climate record. Climate change researchers often use observations from many hundreds, even thousands, of stations that they cannot or do not visit in person, and for which site metadata are often lacking. Information on the surrounding exposure and surface conditions of such stations is generally vague or incomplete. Davey and Pielke (2005) concluded this for the U.S. Historical Climate Network, and we contend that the situation is no better in other parts of the world. Many climatologists instead use surrogate measures of surface cover and exposure in their attempts to classify actual ground conditions at poorly documented sites, and especially to differentiate between "urban" and "rural" stations. These measures—which include population data (e.g., Karl et al. 1988), satellite-derived vegetation indices (Gallo et al. 1993), and night-light frequencies (Hansen et al. 2001; Peterson 2003)—are not reliably linked to local site conditions. This provoked a leading global change scientist (Peterson 2003, p. 2957) to say, "As a community, we need to update our understanding of urban heat islands, to realize that this phenomenon is more complex than widely believed by those not immersed in the field."

Reconstructing a climate station's LCZ history through archival techniques could reveal surface influences on long-term temperature trends that might otherwise have remained unknown (e.g., Runnalls and Oke 2006). At sites where historical temperature records are unavailable, one should instead consult, or construct, an LCZ history of the area to infer temperature trends back into the past.

Architecture, city planning, and landscape ecology. To date, the integration of urban climate knowledge with city planning has not been especially useful or successful, in part because urban climatology has advanced slowly around issues of scale and communication (Oke 1984, 2006; Mills 2006). The LCZ system could advance these issues because it offers a basic package of urban climate principles for architects, planners, ecologists, and engineers. The system conveys these principles through spatial scales (micro, local) and design elements (e.g., building height, "green" cover ratio) that are relevant to the many cognate disciplines of urban climatology. The LCZ system could also support well-established planning projects such as "climatope maps" (Scherer et al. 1999) and "urban climatic maps" (Ren et al. 2011). To help quantify the thermal and morphological layers of an urban climatic map (or UCMap), standardized metadata for urban structure, cover, fabric, and metabolism can be extracted from the LCZ datasheets and adapted to a specific area. LCZs should not, however, be used for climatic mapping alone because, unlike climatopes, they are developed from generalized knowledge of built forms and land cover types that are universally recognized, not from specialized knowledge of local topography and climatology in individual cities. A more appropriate use for LCZs is to build spatial databases of urban form and cover—and the associated effects on thermal climate—for cities worldwide.

CONCLUSIONS. We present local climate zones as a comprehensive climate-based classification of urban and rural sites for temperature studies. The cultural and geographic appeal of the classification has been demonstrated, as has the potential to improve consistency and accuracy in urban climate reporting. The system functions easily and inexpensively in any city or region. We therefore anticipate that it can meet a basic requirement in urban climate studies through standardized description of surface structure and cover; meaningful definition and intercity comparison of UHI magnitude ($\Delta T_{\text{LCZ X - Y}}$); guided exploration of heat island causes and controls; clear communication of site metadata; and interdisciplinary transfer of urban climate knowledge. Our primary motive behind the system, however, is to enhance the description of surface conditions in urban and rural areas, and thereby ease the process of site selection and metadata reporting.

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APPENDIX: SAMPLE DATASHEETS FOR LOCAL CLIMATE ZONES.

LCZ KEY | **ZONE NAME** | **#**

ZONE DEFINITION

Form: Description of building geometry, construction materials, land cover, tree density, and human activity. ***Function***: Land uses most likely associated with this zone. ***Location***: Expected location of the zone (core, periphery; city, countryside). ***Correspondence***: Comparable zones in the urban classification systems of Oke (2004) and Ellefsen (1990/91).

ZONE ILLUSTRATION

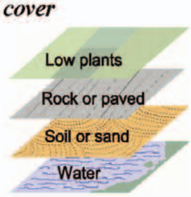
Objects

Buildings heavy materials

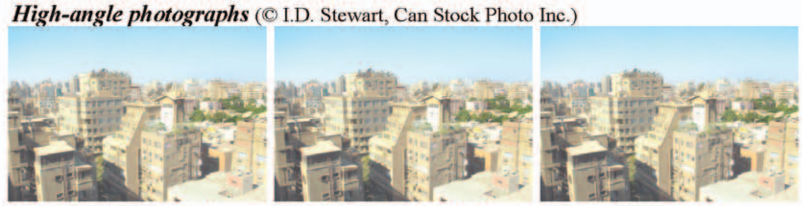
Dwellings lightweight materials

Trees/plants

Land cover



High-angle photographs (© I.D. Stewart, Can Stock Photo Inc.)



Low-level photographs (© I.D. Stewart, Can Stock Photo Inc.)

ZONE PROPERTIES

Sky view factor ψ_{sky} 0 – 1	Fraction of sky hemisphere visible from ground level. Varies with height and spacing of buildings and trees. Affects surface radiational heating/cooling.
Aspect ratio H/W 0 – 3⁺	Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G). Affects surface airflow and radiational heating/cooling.
Mean building/tree height z_H 0 – 50⁺ m	Geometric average of building heights (LCZs 1–10) and tree/plant heights (LCZs A–F). Affects surface reflectivity, flow regimes, and heat dispersion above ground.
Terrain roughness class 1 – 8	Davenport *et al.* (2000) classification of effective terrain roughness (z_0) for city and country landscapes. Affects surface reflectivity, flow regimes, and heat dispersion above ground. See Table 5 for class descriptions.
Building surface fraction λ_b 0 – 100 %	Proportion of ground surface with building cover. Affects surface reflectivity, flow regimes, and heat dispersion above ground.
Impervious surface fraction λ_i 0 – 100 %	Proportion of ground surface with impervious cover (paved or rock). Affects surface reflectivity, moisture availability, and heating/cooling potential.
Pervious surface fraction λ_v 0 – 100 %	Proportion of ground surface with pervious cover (bare soil, vegetation, water). Affects surface reflectivity, moisture availability, and heating/cooling potential.
Surface admittance μ 500 – 2,500⁺ $J\,m^{-2}\,s^{-1/2}\,K^{-1}$	Ability of surface to accept or release heat at local scale. Affects surface heat storage and heating/cooling rates. Varies with soil wetness and material density. In dense tree canopies (LCZ A), the "surface" is undefined and admittance is unknown.
Albedo α 0.02 – 0.5	Surface reflectivity at local scale and under a clear midday sky. Affects surface radiational heating potential. Varies with surface color, wetness, and roughness.
Anthropogenic heat flux Q_F 0 – 400⁺ $W\,m^{-2}$	Mean annual anthropogenic heat flux density at local scale. Heat sources include vehicle engines, industrial/domestic combustion processes, space cooling/heating, and human metabolism. Varies significantly with latitude, season, and population density.

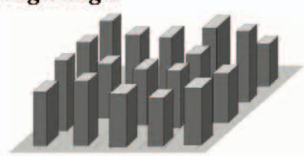
LCZ COMPACT HIGH-RISE 1

DEFINITION

Form: Dense mix of tall buildings to tens of stories. Buildings free-standing, closely spaced. Buildings variable in height. Sky view from street level significantly reduced. Steel, concrete, and glass construction materials. Land cover mostly paved. Few or no trees. High space heating/cooling demand. Heavy traffic flow. ***Function***: Commercial (office buildings, hotels); residential (apartment towers). ***Location***: Core (central business district, "downtown"); periphery. ***Correspondence***: UCZ1 (Oke 2004); Dc1 and Dc8 (Ellefsen 1990/91).

ILLUSTRATION

High angle



Low level

PROPERTIES

Sky view factor
0.2 – 0.4

Canyon aspect ratio
> 2

Mean building height
> 25 m

Terrain roughness class
8

Building surface fraction
40 – 60 %

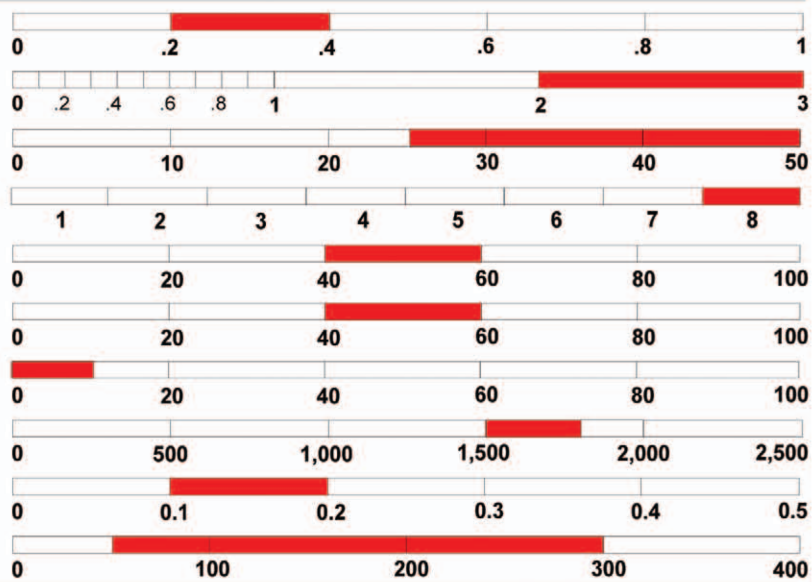
Impervious surface fraction
40 – 60 %

Pervious surface fraction
< 10 %

Surface admittance
1,500 – 1,800 J m^{-2} s$^{-1/2}$ K^{-1}

Surface albedo
0.10 – 0.20

Anthropogenic heat flux
50 – 300 W m^{-2}



LCZ OPEN LOW-RISE 6

DEFINITION

Form: Small buildings 1–3 stories tall. Buildings detached or attached in rows, often in grid pattern. Sky view from street level slightly reduced. Construction materials vary (wood, brick, stone, tile). Scattered trees and abundant plant cover. Low space heating/cooling demand. Low traffic flow. ***Function***: Residential (single or multi-unit housing, low density terrace/row housing); commercial (small retail shops). ***Location***: City (medium density); periphery ("suburbs"). Commuter towns. Rural towns. ***Correspondence***: UCZ5 (Oke 2004); Do3 (Ellefsen 1990/91).

ILLUSTRATION

PROPERTIES

Sky view factor
0.6 – 0.9

Canyon aspect ratio
0.3 – 0.75

Mean building height
3 – 10 m

Terrain roughness class
5 – 6

Building surface fraction
20 – 40 %

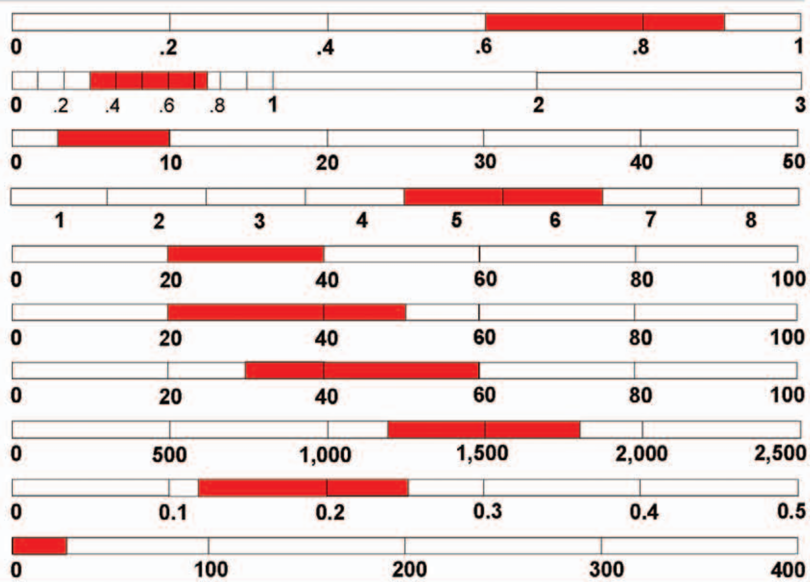
Impervious surface fraction
20 – 50 %

Pervious surface fraction
30 – 60 %

Surface admittance
1,200 – 1,800 J m^{-2} s$^{-1/2}$ K^{-1}

Surface albedo
0.12 – 0.25

Anthropogenic heat flux
< 25 W m^{-2}



LCZ — Low Plants — D

Definition

Form: Featureless landscape of pervious ground, predominantly low plant cover. Few or no trees, roads, or buildings. Full sky view from ground level. Space heating/cooling demand nil. Low or no traffic flow. ***Function***: Natural grassland (savannah, steppe). Agriculture (pasture, arable farmland). Urban recreation (open, grassy parks and green spaces). ***Location***: City or country. ***Correspondence***: UCZ7 (Oke 2004).

Illustration

High angle

Low level

Properties

Sky view factor
> 0.9

Tree aspect ratio
< 0.1

Mean plant height
< 1 m

Terrain roughness class
3 – 4

Building surface fraction
< 10 %

Impervious surface fraction
< 10 %

Pervious surface fraction
> 90 %

Surface admittance
1,200 – 1,600 J m^{-2} s$^{-1/2}$ K^{-1}

Surface albedo
0.15 – 0.25

Anthropogenic heat flux
0 W m^{-2}