1.1 THERMAL DIFFERENTIATION OF LOCAL CLIMATE ZONES USING TEMPERATURE OBSERVATIONS FROM URBAN AND RURAL FIELD SITES

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1. PAST WORK: DEVELOPING A CLIMATE-BASED LANDSCAPE CLASSIFICATION SYSTEM

1.1 *Background*

Urban climatology is a rapidly growing field. Standards are therefore necessary to ensure consistent and meaningful exchange of data across regions, cultures, and disciplines. In recent years, the use of common scales and techniques in urban climatology has greatly improved communication (Oke, 2006). However, one aspect of communication not yet standardized is the description of urban and rural field sites. The traditional ad hoc approach to site description has created much confusion in urban climate literature, as inter-city comparisons of results are rarely substantiated by the physical properties of the urban and rural field sites. In a recent review of modern heat island literature, Stewart (in press) cites "completeness of reporting" as an area of universal weakness. The tendency of heat island investigators to attach inappropriate or insufficient site metadata to their reports is the primary cause of this weakness. Of the 190 sample papers evaluated in the review, 88% failed to provide quantitative descriptors of the urban and rural field sites used to define heat island magnitude. Thirty-three percent of the sample papers gave no description whatsoever (qualitative or quantitative) of their urban and rural field sites.

These statistics expose a critical gap in the portrayal of city and country landscapes in urban climate literature. This gap has received little attention among urban climatologists despite early indications from Luke Howard—the nineteenth-century pioneer of heat island research—that a common tongue among all meteorologists is necessary for rapid scientific progress (Howard, 1833). One hundred and fifty years later, modern investigators like Chandler (1970) and Böhm and Gabl (1978) urgently called for "international standards" in urban climate reporting. Aguilar et al. (2003) and Oke (2004) responded with comprehensive WMO guidelines for siting meteorological instruments in cities, and Ellefsen (1990/1) and Oke (2004) developed new classification systems for characterizing the urban environment. These systems have served the discipline well but were never purported to characterize a full range of urban and rural landscapes. Ellefsen and Oke did, however, provide the necessary groundwork for a more universal scheme later proposed by Stewart and Oke (2006, 2009a). This scheme has since become the "local climate zone" classification system.

1.2 *Local Climate Zones*

Local climate zones (LCZ) are defined as regions of uniform surface-air temperature distribution at horizontal scales of 10^2 to 10^4 metres (Stewart and Oke, 2009b). Each LCZ exhibits a characteristic geometry and land cover that generates a unique surface-temperature climate under calm, clear skies. The zones are differentiated by surface properties that directly influence screen-height temperature, such as vegetative fraction, building/tree height and spacing, soil moisture, and anthropogenic heat flux. By these differentiae, the urban-rural continuum yields a hierarchy of 16 climate zones (Figure 1).

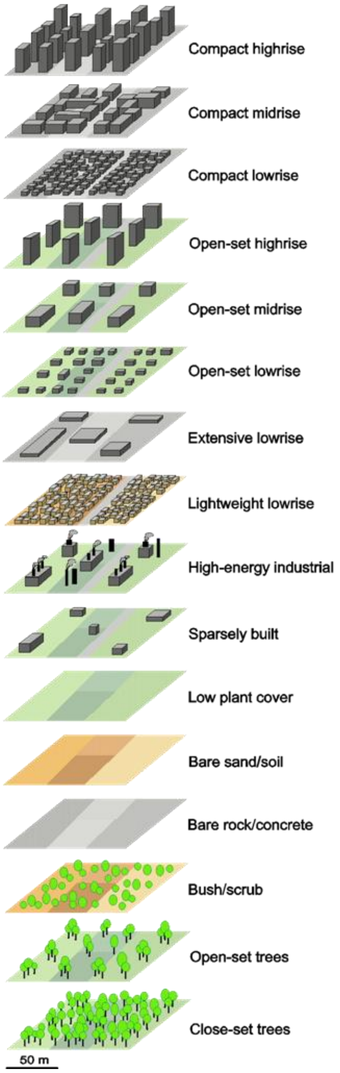

Figure 1: Local climate zones.

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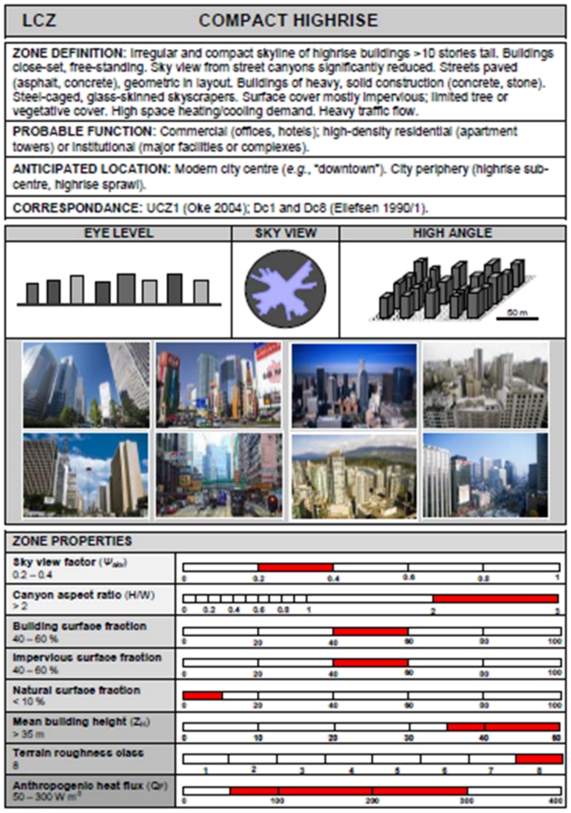
The surface properties of each zone are described and illustrated in standardized data sheets (e.g., Figure 2).



LCZ **COMPACT HIGHRISE**

ZONE DEFINITION: Irregular and compact skyline of highrise buildings >10 stories tall. Buildings close-set, free-standing. Sky view from street canyons significantly reduced. Streets paved (asphalt, concrete), geometric in layout. Buildings of heavy, solid construction (concrete, stone). Steel-caged, glass-skinned skyscrapers. Surface cover mostly impervious; limited tree or vegetative cover. High space heating/cooling demand. Heavy traffic flow.

PROBABLE FUNCTION: Commercial (offices, hotels); high-density residential (apartment towers) or institutional (major facilities or complexes).

ANTICIPATED LOCATION: Modern city centre (e.g., "downtown"). City periphery (highrise sub-centre, highrise sprawl).

CORRESPONDANCE: UCZ1 (Oke 2004); Dc1 and Dc8 (Ellefsen 1990/1).

ZONE PROPERTIES

Sky view factor (Ψ_{sky}) 0.2 – 0.4

Canyon aspect ratio (H/W) > 2

Building surface fraction 40 – 60 %

Impervious surface fraction 40 – 60 %

Natural surface fraction < 10 %

Mean building height (Z_H) > 35 m

Terrain roughness class 8

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

Figure 2: Datasheet for *compact highrise*.

The LCZ classification system encourages urban climatologists to give quantitative site metadata with their reported findings, and to communicate those metadata in a standardized manner. Standardized metadata in turn facilitates inter-city comparisons of results. LCZs should therefore apply reasonably well in all regions of the world regardless of cultural or physical setting. LCZs should also be easy to interpret for all climate researchers, and especially for those who have limited resources to classify sites or carry out sophisticated observations.

In bringing the LCZ system to its current form, extensive feedback was solicited from the international climate and planning communities. Prototype datasheets and LCZ sketches were distributed to research groups worldwide in exchange for critical feedback on the general nature and scope of the LCZ system, its ease of use, its application to local settings, and its perceived cultural and regional biases. The system has further benefited from a pilot run on the *Urban Flux Network* (http://www.geog.ubc.ca/urbanflux), an IAUC-hosted database for cataloguing urban micrometeorological tower sites. With this international exposure, the LCZ system has moved closer to a design of universal appeal.

Whilst the LCZ classification system is theoretically sound in its division of the landscape on surface climate properties, it has little empirical evidence to support that division. Thus the purpose of the present paper is to assess the validity of the LCZ division using temperature observations from three representative city-regions of Europe, East Asia, and North America. The results of this assessment suggest that the LCZ system is nearing its optimal form, but that further enhancements to individual classes are needed.

2. PRESENT WORK: THERMAL DIFFERENTIATION OF LOCAL CLIMATE ZONES

2.1 *Test locations*

Three test locations were used to differentiate LCZs: Uppsala, Sweden (59°N, 17°E); Nagano, Japan (36°N, 138°E); and Vancouver, Canada (49°N, 123°W). These locations include a variety of urban and rural landscapes that are characteristic of the observational urban climate literature. Uppsala is a traditional European city with a flat building profile, a compact core, and a clearly defined urban-rural boundary. Nagano is a typical medium-sized East Asian city with intensely mixed urban and agricultural land uses, both within and outside the city. Vancouver is a large North American city with a modern highrise core, low-density residential areas, and an extensive urban forest. The mid-latitude climates of the three test locations are ideal for investigating the seasonal effects of snow, tree canopy coverage, soil moisture, and anthropogenic heat flux on LCZ formation. Furthermore, each city has a long tradition of urban climate research and is the site of many reputable heat island studies. Raw temperatures can be extracted from these studies and used to differentiate LCZs.

Surface relief in Uppsala and Nagano is slight. Local temperature variations in the study area are thus not complicated by the effects of cold-air drainage or elevation change, which does not exceed 30 m. In Vancouver, elevation change reaches 100 m and local relief and water bodies further complicate the urban-rural topography. Temperatures in Vancouver are therefore influenced by a complex mix of urban and topoclimatic factors.

2.2 *Test methods*

Temperature data for Uppsala were obtained from a network of nine fixed stations used by Taesler (1981) from January 1976 to February 1977. These stations were sited in areas of variable building density and surface cover for the purpose of monitoring Uppsala`s canopy-layer heat island. The Nagano temperature data were obtained from the heat island investigations of Sakakibara and Matsui (2005), who conducted 90 automobile traverses across the floor of Nagano basin between December 2001 and November 2002. All traverses started at midnight in central Nagano city and passed through nearby rice fields, orchards, and agricultural towns. The Vancouver data were obtained from evening automobile traverses conducted by students at the University of British Columbia between 1992 and 2010. The traverses supplied data for the heat island field component of an undergraduate urban meteorology course. Under supervision of the course instructor, students used instrumented vehicles to gather temperatures from a traverse route that passed through the major land uses of Vancouver and its countryside. All temperatures in Vancouver, Nagano, and Uppsala were measured with a precision of ±0.2°C and at standard screen height of 1–2 m above ground.

Representative field sites from each of the three test locations were selected and classified into LCZs. Sites were considered "representative" only if the surrounding circle of influence, or source area, was relatively uniform in surface cover, geometry, and human activity. Anomalous micro-scale features along the traverse route, such as bridges, parks, shopping malls, and major intersections, were therefore avoided during site selection. The circle of influence is difficult to quantify, but observational evidence suggests that a radius of 100–200 m, depending on building density and boundary-layer conditions, is appropriate for screen-height measurements (Runnalls and Oke, 2006). The circle of influence was parameterized by the physical properties associated with each LCZ (see datasheet, Figure 2). The reader is referred to Stewart and Oke (2009b) for a fuller account of the LCZ classification process.

Several sources of metadata were used to parameterize each field site. These include published heat island investigations in the three cities, personal communication with the original investigators, land-use and land-cover maps, and images from Google Earth / Maps. In addition, each city was visited in person to further observe and document the surface features of the original sites. After the sites were parameterized, the traverse datasets were filtered by strict weather criteria to capture maximum thermal contrasts among LCZs, and to control advection of thermal properties across zone boundaries. These criteria stipulate (a) calm or light winds during the traverse, (b) clear skies or high-level cloud in the hours preceding the traverse, and (c) no significant precipitation on the day of the traverse. These wind and cloud conditions correspond to a weather factor (Φ_W) of >0.7, depending on cloud type (see Oke [1998] for explanation of Φ_W). Ancillary weather data for filtering the traverses were obtained from local meteorological offices in the three test locations.

2.3 *Test results*

A partial but representative sample of results from Uppsala, Nagano, and Vancouver is presented here. The hours, days, years, and field sites in this sample are characteristic of the original source data and provide a reliable basis for LCZ thermal differentiation. LCZs are differentiated through daily extrema, diurnal temperature range (DTR), and synchronous hourly temperatures.

2.3.1 Uppsala, Sweden

September 20–23, 1976, was a favorable period for LCZ differentiation in Uppsala. The prevailing weather was dry, calm, and clear, and thus LCZ surfaces were highly responsive to thermal change. The temperature-time series for this 3-day period shows that thermal differences among LCZs vary with time of day (Figure 3a). Temperatures across the five LCZs are approximately equal from sunrise to noon, but differentiate slightly in the afternoon as *compact midrise* and *low plant cover* become the warmest zones. After sunset, the LCZ profiles stratify and eventually reach maximum differentiation just before sunrise, at which point each LCZ differs by 1–2°C. A total difference of 5°C separates the warmest (*compact midrise*) and coolest (*low plant cover*) zones. Only the *open-set lowrise* and *sparsely built* zones fail to differentiate during the 3-day sample period.

LCZs are further differentiated through daily extrema (Figure 3b). Most striking is the cooling trend in daily minima from *compact midrise* to *low plant cover*, as nighttime lows drop by 1–2°C with each successive zone and with increasingly open building-geometries and natural-surface fractions. The *sparsely built* zone appears out of step with this trend, with daily minima 0.5°C warmer than *open-set lowrise*. The open-set tree canopy in the *sparsely built* zone may account for this discrepancy. The DTRs in each of the five zones follow an opposite but less dramatic trend. The smallest and largest DTRs are found in *compact midrise* and *low plant cover*, respectively. DTR in *low plant cover* is 4°C greater than both *compact midrise* and *open-set midrise*, and 3°C greater than *open-set lowrise* and *sparsely built*. Trends in daily maxima among all zones are less apparent than in daily minima or DTR, except that *compact midrise* and *low plant cover* reached daytime highs of 1–2°C above all other zones. The tree canopy of the *sparsely built* zone has likely moderated daily extrema, with daytime highs cooler than those of the treeless *low plant cover*. *Compact midrise* has the highest daily maxima at 0.5–2.5°C above all other zones.

2.3.2 Nagano, Japan

The Nagano traverses were stratified into three seasons, each corresponding with a distinct rural soil-cover and field-moisture regime: (1) flooded fields in spring/summer (May–June), (2) drained fields in winter (December–March), and (3) snow-covered fields in winter (December–January). Overall, departures from the mean traverse temperatures in each successive zone follow a step-like pattern, such that *compact highrise* is 2°C warmer than both *compact lowrise* and *open-set lowrise*, and 3°C warmer than *low plant cover* and *open-set trees* (Figure 4). In spring\summer, the warmest LCZ in the Nagano basin is *compact highrise*, and the coolest LCZ is *open-set trees*. In winter, the coolest LCZ is *low plant cover*.

Seasonal effects on LCZ differentiation are insignificant in the two compact built zones, but are sharper further down the hierarchy as the zones become increasingly natural in composition. At the rural sites, inter-seasonal differences in temperature departures are greater than inter-zone differences.

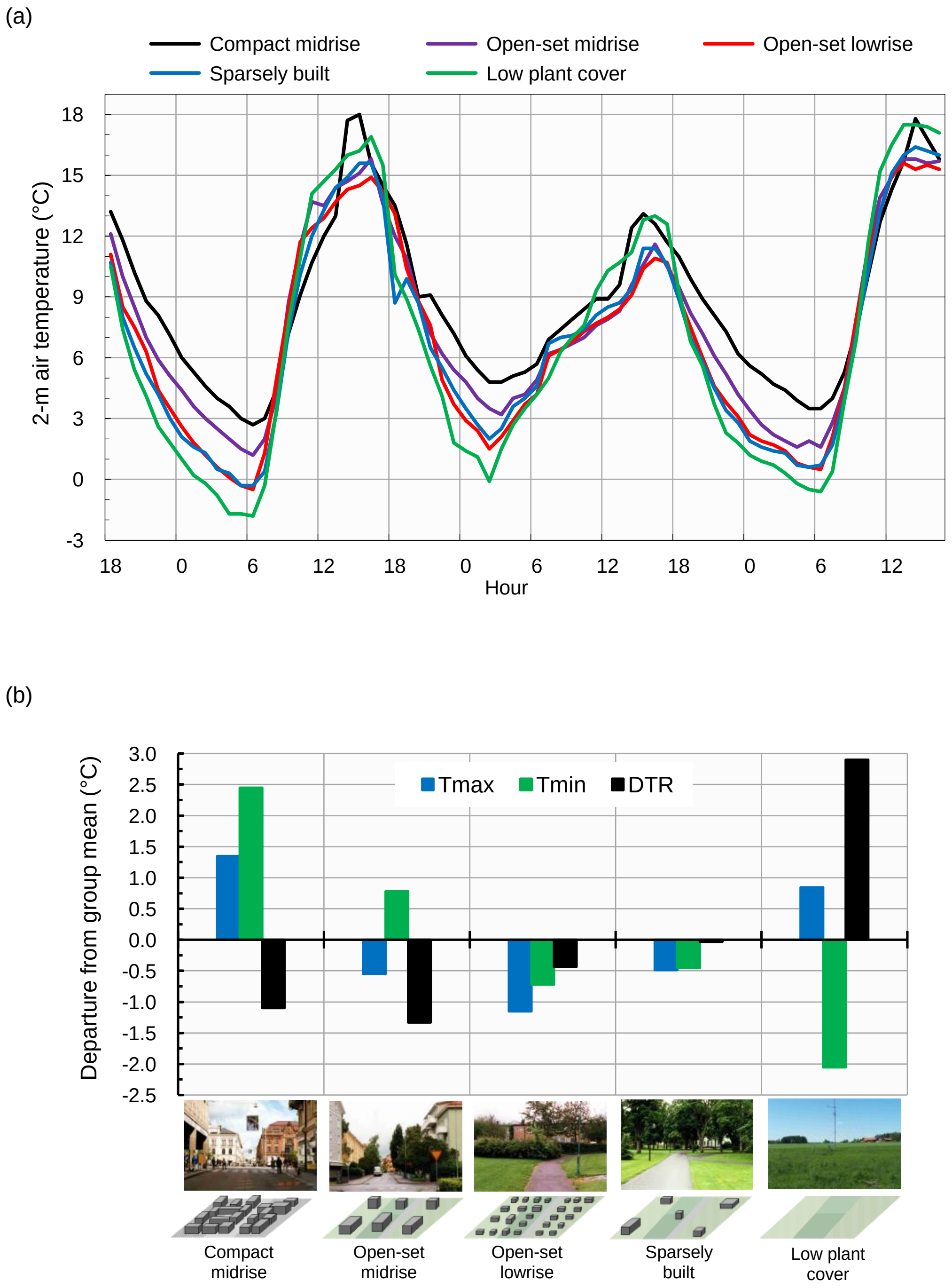


Figure 3: Thermal differentiation of local climate zones in Uppsala, 21–23 September 1976: (a) hourly temperatures (*sunrise* = 0550 hr; *sunset* = 1815 hr); (b) daily extrema. Data source: Taesler (1981).

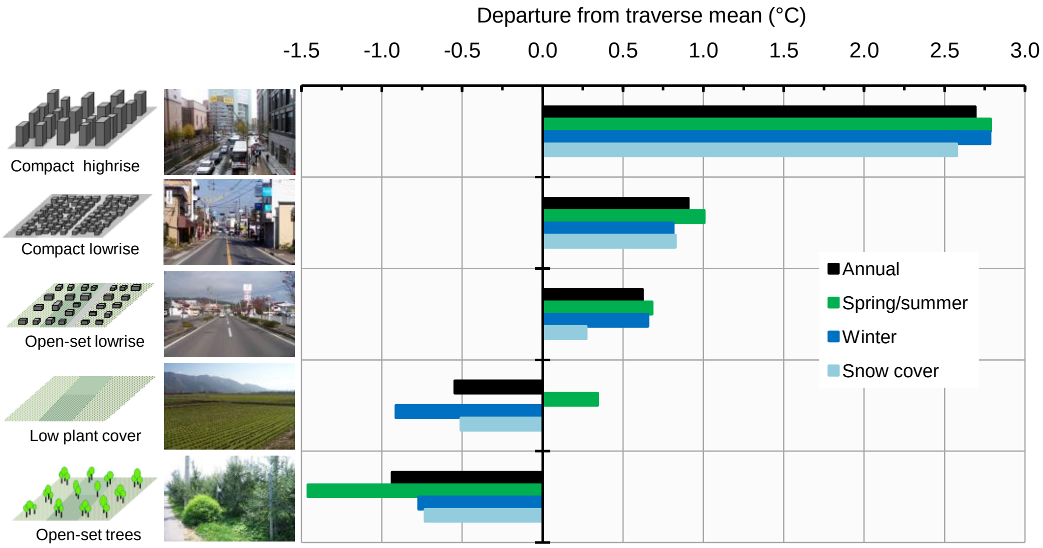


Figure 4: Thermal differentiation of local climate zones in Nagano basin (2001–02) at 0000 hr (*Annual* = 32 cases; *Spring/summer* = 5 cases; *Winter* = 10 cases; *Snow cover* = 3 cases). Data source: Sakakibara and Matsui (2005).

Temperatures in *low plant cover* and *open-set trees* are strongly influenced by seasonal change in soil cover, field moisture, and fractional tree-canopy coverage. However, only *open-set lowrise* shows a slight cooling effect from snow cover.

Marked seasonal changes occur in spring/summer when fields in *low plant cover* are flooded for rice cultivation, and the fractional canopy coverage of *open-set trees* increases with leaf emergence (Figure 4). The wet soils of *low plant cover* cause noticeable warming in the temperature departures for spring/summer, as shown by a positive (1.5°C) shift from the winter values. In *open-set trees*, the spring/summer leaf canopy has a cooling effect (relative to the leafless winter canopy) on air temperatures. This is manifest through a negative (0.5–1°C) shift from the traverse mean. Finally, in *low plant cover*, snow has a slight warming influence relative to winter drained soils, and a slight cooling influence relative to spring/summer wet soils. Conversely, in *open-set trees*, snow has a warming influence on temperature departures relative to spring/summer wet soils, and no influence relative to winter drained soils.

2.3.3 Vancouver, Canada

Cross-sectional temperature profiles for three representative nights in 1999 are shown in Figure 5. The profiles show consistent thermal patterns through the LCZs of Vancouver. Temperatures “spike” and “dip” as the traverse moves through LCZs of variable surface geometry and cover. For example, as the traverse moves away from the downtown core (*compact highrise*) and into a heavily forested park (*close-set trees*), the temperature drops sharply by 4°C. The temperature again drops when the traverse passes from *open-set lowrise* to *sparsely built*. All sites in *open-set lowrise* take an intermediate position along the profile, that is, they are cooler than *compact highrise* but warmer than both *close-set trees* and *low plant cover*. Temperatures in *compact highrise* are 6–7°C warmer than *low plant cover*.

Vehicle traverses in 2008–10 passed through a greater diversity of LCZs than in 1999. Due to the extensive urban forest in Vancouver, two of the nine sampled LCZs are sub-classified by tree geometry (Figure 6). In addition, temperature departures at two control sites in each LCZ are plotted separately so as to control for differential topoclimatic effects. Each pair of control sites is similar in building/tree geometry, but slightly different in local relief, elevation, and/or vegetation. In most cases, intra-zone temperature differences between the two control sites are minimal (<0.5°C), suggesting that topoclimatic effects have been sufficiently controlled through strategic site-selection. Confidence can thus be put in the thermal differentiation of LCZs in Vancouver despite the city`s complex physical setting. Only in the open-set LCZs do the control sites deviate by more than 0.5°C.

In general, the LCZ hierarchy in Vancouver cools progressively—but not linearly—from highrise and compact built zones at the top, to open and treed natural zones at the bottom (Figure 6). Lowrise and open-set zones span a conservative range of temperatures. The largest temperature drop between successive zones is 1.5°C, from *compact highrise* to *open-set highrise*, and from *low plant cover* to *close-set trees*. The effects of tree geometry on temperatures in the built zones are not obvious. The two *open-set lowrise* zones are significantly different in tree geometry, but are similar in temperature departures from the traverse mean.

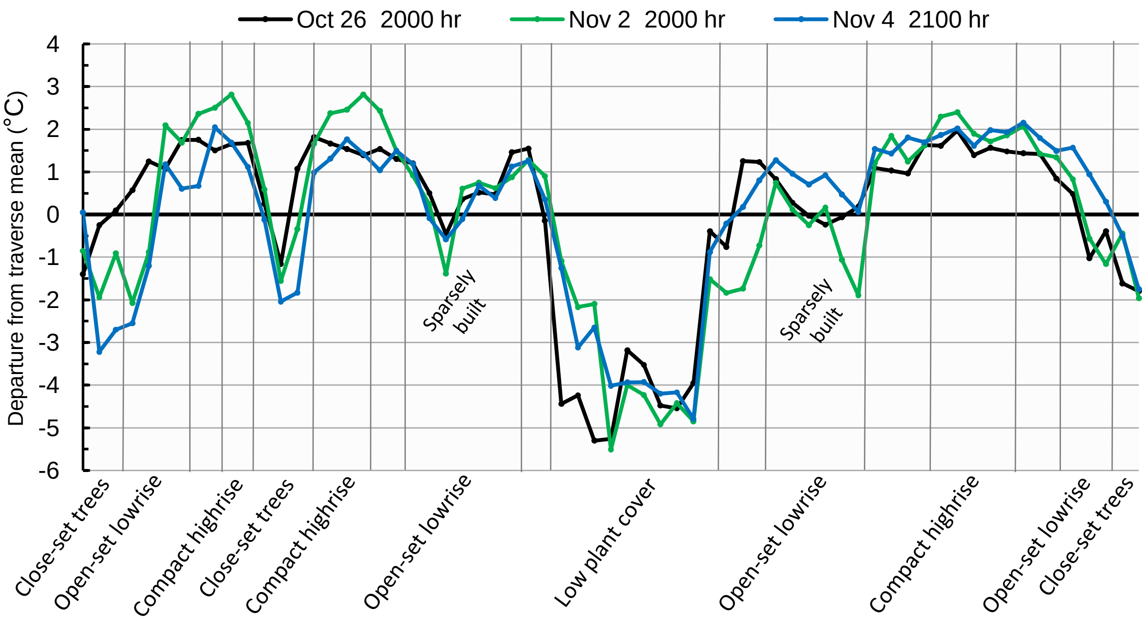


Figure 5: Temperature cross-sections through local climate zones in Vancouver, 1999.

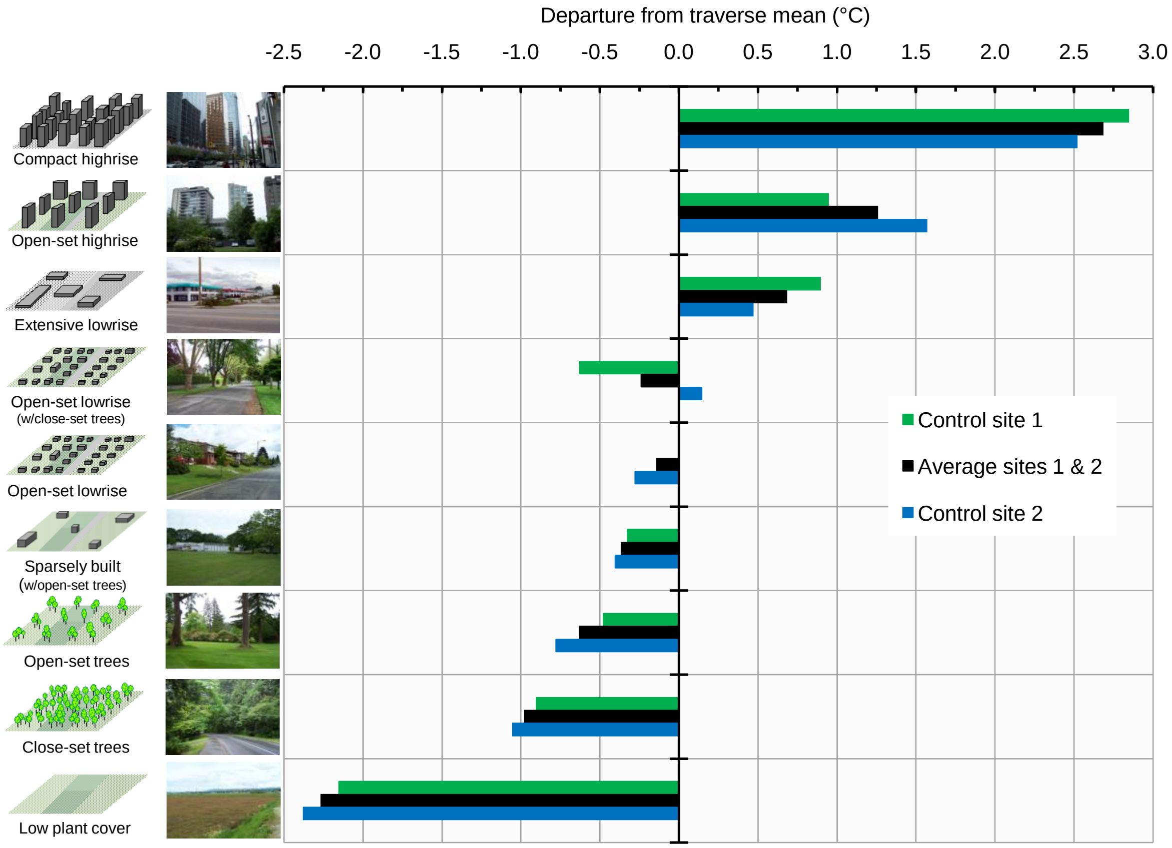


Figure 6: Thermal differentiation of local climate zones in Vancouver based on evening traverses in March 2008 and 2010 (4 cases).

3. FUTURE WORK: ENHANCING THE LOCAL CLIMATE ZONE CLASSIFICATION SYSTEM

This paper has shown that observed temperatures from heat island studies in Uppsala, Nagano, and Vancouver broadly support the hierarchical structure of the local climate zone system. As expected, top-down cooling through the hierarchy is driven largely by building morphology and natural surface fraction. During calm and clear evenings, thermal differentiation of LCZs varies with the degree of structural and material separation between zones. Temperature differences among zones of large separation, such as *compact midrise* and *low plant cover*, can exceed 5°C. Between zones of lesser separation, like *compact highrise* and *open-set highrise*, temperature differences are significantly reduced but still apparent, ranging from <0.5 to 2°C. These patterns are easily disrupted, however, by the seasonal effects of soil moisture, tree geometry, and snow cover, which can override or offset the unvarying effects of building geometry or natural surface fraction. Seasonal effects are especially important among zones of a transitional nature (i.e., urban-rural), such as *open-set lowrise* and *sparsely built*, which are both poorly differentiated in the Uppsala and Vancouver datasets. Final revisions to this standard set of local climate zones must therefore take into account the effects of soil moisture, tree geometry, and snow cover on the divisional structure and explanatory power of the LCZ system.

With these results, the local climate zone classification system moves closer to completion. It now awaits output from computer models to further test the robustness of its class properties (e.g., Krayenhoff et al., 2009). Meanwhile, observational results herein have demonstrated the cultural and geographic appeal of the LCZ system—through standardized portrayal of urban and rural landscapes in Europe, East Asia, and North America—and its potential to improve consistency and accuracy in urban climate reporting. We anticipate a broad range of uses for the LCZ system, from urban terrain and climate mapping, to the detection of urban bias in regional climate-station networks. Our primary motive, however, is to promote greater methodological rigor in the reporting of canopy-layer heat islands and urban microclimates.

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REFERENCES

Aguilar E, Auer I, Brunet M, Peterson TC, and J Wieringa, 2003. *Guidance on Metadata and Homogenization*. WMO Technical Document No. 1186. World Meteorological Organization: Geneva.

Böhm R, and K Gabl, 1978. The urban heat island in dependence of different meteorological parameters. [In German.] *Archives for Meteorology, Geophysics, and Bioclimatology B* 26: 219–37.

Chandler TJ, 1970. Urban climatology – Inventory and prospect. In *Urban Climates – Proceedings of the Symposium on Urban Climates and Building Climatology, October 1968, Brussels*. WMO Technical Note No. 108. World Meteorological Organization: Geneva.

Ellefsen R, 1990/1. Mapping and measuring buildings in the urban canopy boundary layer in ten US cities. *Energy & Buildings* 15-16: 1025–1049.

Howard L, 1833. *The Climate of London*. Dalton: London.

Krayenhoff S, Stewart ID, and TR Oke, 2009. Estimating thermal responsiveness of local-scale climate 'zones' with a numerical modeling approach. Preprints*, Eighth Symposium on the Urban Environment,* January 11–15, Phoenix, AZ.

Oke TR, 1998. An algorithmic scheme to estimate hourly heat island magnitude. Preprints, *Second Symposium on Urban Environment,* November 2–5, Albuquerque, NM.

Oke TR, 2004. *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*. IOM Report 81, World Meteorological Organization, Geneva.

Oke TR, 2006. Towards better scientific communication in urban climate. *Theoretical and Applied Climatology* 84: 179–190.

Runnalls KE, and TR Oke, 2006. A technique to detect microclimatic inhomogeneities in historical records of screen-level air temperature. *Journal of Climate* 19: 959–978.

Sakakibara Y, and E Matsui, 2005. Relation between heat island intensity and city size indices/urban canopy characteristics in settlements of Nagano basin, Japan. *Geographical Review of Japan* 78: 812 – 824.

Stewart ID, and TR Oke, 2006. Methodological concerns surrounding the classification of urban and rural climate stations to define urban heat island magnitude. Preprints*, Sixth International Conference on Urban Climate,* June 12–16*,* Goteborg, Sweden.

Stewart ID, and TR Oke, 2009a. Conference notebook– A new classification system for urban climate sites. *Bulletin of the American Meteorological Society* 90: 922–923.

Stewart ID, and TR Oke, 2009b. Classifying urban climate field sites by "local climate zones": The case of Nagano, Japan. Preprints*, Seventh International Conference on Urban Climate,* June 29–July 3, Yokohama.

Stewart ID, in press. A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology.* DOI: 10.1002/joc.2141

Taesler R, 1981. *Studies of the Development and Thermal Structure of the Urban Boundary Layer in Uppsala.* Meteorological Institute (Uppsala University), Report No. 61.