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A Study of Urban Heat Island using "Local Climate Zones" – The Case of Singapore

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

Aims: The study of urban heat islands and traditionally relies on simplistic descriptors such as "urban" and "rural". While these descriptors may be evocative of the landscape, they are insufficient in providing information like its site properties which have direct impacts on the surface-layer climate. The newly developed "Local Climate Zones" (LCZ) characterization scheme from Oke and Stewart [1] was applied to three case study areas to provide a more objective assessment of the urban heat island (UHI) phenomenon in Singapore.

Study Design: The three step procedure of site metadata collection, definition of the thermal source area, and selection of the appropriate climate zone was followed for the three case study areas representing green space, a typical high rise residential housing area, and the CBD to identify and explain UHI characteristics.

Place and Duration of Study: Singapore; January-March, 2014.

Methodology: Characterization of the three study sites included scoring of a sky view factor, canyon aspect ratio, terrain roughness, building surface fraction, impervious surface fraction, surface energy admittance, surface albedo, and anthropogenic heat flux based on observation, photography, and Google Earth imagery, to determine the LCZ class. Temperature, wind speed, and relative humidity were recorded on an hourly basis at each site using Kestrel 4000 weather trackers and data logger at a 2 m elevation for five consecutive days in January, 2014.

Results: The three study sites were characterized as LCZ 1 (compact high rise (CBD)), LCZ 4 (open high rise (high rise residential housing area)), and LCZ 9 (sparsely built (green space)). The temperature for LCZ 9 was lower than the other two sites, with the greatest UHI intensity (difference between mean air temperature being 2.01°C between LCZ 4 and LCZ 9. Interestingly, although the CBD area was warmer than the open high rise area between midnight and 6 a.m., a

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typical UHI phenomenon, the mean air temperature for the entire 5 day period was greater at the open rise site.

Conclusion: The lower temperature at the green space site emphasizes the importance of such spaces in the urban landscape as a means to make cities more liveable and resilient to climate change impacts. The higher mean temperature at the open high rise site as compared to the CBD site was related to anthropogenic activities (particularly traffic patterns), landscaping/green space, and the influence of a large green-certified building within the circle of influence at the CBD site. Overall, the use of LCZ in quantifying the UHI magnitude of Singapore was relatively straightforward to apply and this approach should be widely applied to more objectively investigate the UHI phenomenon, particularly in tropical cities.

Keywords: Singapore; local climate zones; urban and rural; tropical urban climate; Urban Heat Island (UHI); Central Business District (CBD); green space.

1. INTRODUCTION

The study of urban climate has been ongoing for more than three decades, but recently, the world has seen its climate change in terms of the occurrence of natural catastrophes and the rise in temperatures. According to World Health Organization [2], more than half of the world population lives in urban areas. It is estimated that 60% of the world's population will live in cities in the year 2025 [3,4]. This entails a greater population density and spatial cover which has the tendency of contributing to climate change. These two of the most serious environmental issues of the twentieth century - population growth and climate change - have led to increasing interest in the urban heat island (UHI) phenomenon in recent years [1]. Whilst the study of UHI has come a long way, it has a rather discouraging outlook as 75% of the publications related to UHI failed to quantify site exposure and land cover [5,6,7]. Fifty percent of the published studies failed to control for non-urban effects on UHI and twenty-five per cent of the published studies failed to define "UHI magnitude" (a phenomenon where urban regions experience higher temperature than their rural regions) [5]. Furthermore, the majority of the published UHI magnitudes from around the world are not scientifically defensible [5]. This has made it difficult to compare UHI characteristics between cities. As such, Oke and Stewart [5] pushed for a protocol to make heat island observations more credible. The most common type of urban heat island scheme involves the use of an urban-rural classification (Fig. 1). Fig. 1 portrays the common trend identified by many studies [8,9,10] where temperatures are significantly warmer in a city than its surrounding rural areas, a phenomenon known as Urban Heat Island (UHI) effect. The thermal contrasts between the urban and rural area can be seen in the stark difference in the temperature, especially at night, "owning to slower cooling of the urban landscape, and during light winds" [11].

While the urban rural classification approach may be evocative of the landscape for certain countries, an underlying problem with urban climate studies is that there is practically no universally accepted scheme of urban classification for climatic purposes. Each city is exposed to diverse local and synoptic factors, which makes the study of the UHI complex and specific to locality [12].

Furthermore, there is vagueness in using the urban rural classification. The term "urban" is commonly used to describe places like towns, city, suburb and metropolitan areas or megacities. As highlighted by Bjelland et al. [13], different parts of the world interpret the term "urban" and "rural" differently. As such, the non-standardized way of classification makes heat island literature difficult to compare between different countries. An apparent problem with the use of such definitions is that there is "no single, objective meaning, thus no climatological relevance" [1]. As a result, different researchers adopt different approaches to the problem, which makes it difficult to determine which factors that control the urban climate are more important in a particular urban context [8]. In addition, in densely populated regions such as Asia, the social, political, and economic space that separates cities and countrysides are no longer distinguished by a clear urban rural demarcation [1]. This makes it even harder to apply the urban rural classification in climate studies.

Therefore, the main objective of this study is to adopt the newly formulated climate scheme – Local Climate Zone (LCZ) proposed by Oke and Stewart [1] to characterize test field sites in

Singapore so as to investigate the temporal variations in the UHI intensity. By doing so, I hope to highlight the importance of green spaces in Singapore. By using the standardized description of surface structure and cover and a standard definition of UHI magnitude (ΔTLCZ X−Y), this work can help to provide a more accurate assessment of urban heat island intensity for future investigations in Singapore and facilitate more rigorous intercomparisons with other Southeast Asian cities.

1.1 Background on the Local Climate Zone (LCZ) Approach

'Local climate zones' (LCZs) is a new and systematic classification of field sites for heat island studies. The classification divides urban and rural landscapes into 17 standard classes, each defined by structural (built) and land cover properties that influence air temperature at a screen height of 1- 2 metres above ground. This framework is the first to evaluate the conceptual division of LCZs with temperature observations and simulation results from surface–atmosphere models. Oke and Stewart [14,1] developed LCZ as a comprehensive climate-based classification of urban and rural sites that facilitates objective comparison of urban climates between cities using standard, routinely collected meteorological data. In this new framework, instead of taking the intra-urban UHI intensity as an "urban-rural" difference (ΔTu–r), an LCZ temperature difference (ΔTLCZ X–Y) is developed [1].

With the new framework, UHI magnitude is an LCZ temperature difference (eg. TLCZ1 - LCZ D), not an urban rural difference (T u-r) and it is less prone to confusion as the common surface and exposure characteristics of the compared field sites are being highlighted [1]. To give a better idea of how the field sites are characterized and classified using this scheme, a sample data sheet has been presented by Oke and Stewart [1] as seen in Fig. 2. The data sheet is broadly categorised into 3 different segments: 1) Zone definition, 2) Zone Illustration and 3) Zone Properties. 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. [1]. There are ten built types (from LCZ 1 to LCZ 10) and seven land cover types (from LCZ A to LCZ G) (see Table 1), and additionally, these types can have variable seasonal or shorter period land cover properties [15].

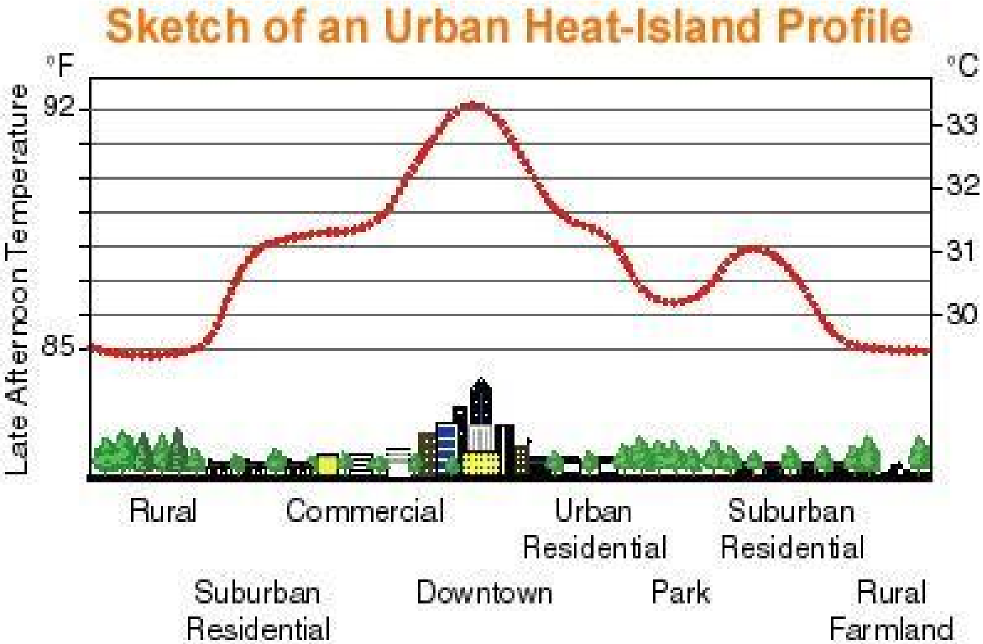

Fig. 1. Sketch of the profile of temperatures typically observed in urban cities using the Urban-Rural classification (Courtesy of the Lawerence-Berkeley National Laboratory in [12])

Table 1. Categories and Characteristics of LCZ [1]

Built types	Land cover types	Variable land cover properties
LCZ 1 – Compact high rise	LCZ A – Dense trees	b – bare trees
LCZ 2 – Compact mid rise	LCZ B – Scattered trees	s – snow cover
LCZ 3 – Compact low-rise	LCZ C – Bush, scrub	d – dry ground
LCZ 4 – Open high-rise	LCZ D – Low plants	w – wet ground
LCZ 5 – Open mid-rise	LCZ E – Bare rock / paved	
LCZ 6 – Open low-rise	LCZ F – Bare Soil / sand	
LCZ 7 – Lightweight low-rise	LCZ G - Water	
LCZ 8 – Large low-rise		
LCZ 9 – Sparsely built		
LCZ 10 – Heavy industry		

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

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
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.

Fig. 2. Sample data sheet using the local climate classification scheme [1]

According to Oke [16], site selection can be usefully refined in the case of air temperature and humidity by conducting spatial surveys, wherein the sensor is carried on foot, or mounted on a bicycle or a car and transversed through areas of interest. Usually, the ideal time to conduct these surveys is a few hours after sunset or sunrise on nights with relatively calm airflow and cloudless skies. This would maximize the potential for the differentiation of micro- and local climate differences [16].

1.2 Background to UHI Studies in Singapore

Singapore is an island-state located between the Southern tip of Malaysia Peninsula and northern tip of Indonesia of Southeast Asia (1°14’ N and 103°55 ‘E) (See Fig. 3). Its geographical area which lies 137 kilometres north of the equator is characterized by tropical climate with uniformly high annual mean temperatures (26 – 27.5ºC) and rainfall (~2300 mm). The highest monthly precipitation values are observed between the months of November and January, and this is associated with the northeast monsoon. The drier seasons are observed during the period between May and July which is associated with the southwest monsoon. On the whole, Singapore’s climate is sometimes divided into four distinct seasons: northeast and southwest monsoons, separated by two brief inter-monsoons [17]. Due to its relatively homogenous topography and small size, there is limited variation in the local synoptic climate [18].

The climate of Singapore has experienced change since 1970s, warming at an average rate of 0.25ºC per decade [19]. The mean sea level of the Singapore Strait has also shown a rise by 3mm per year over the last 15 to 17. As Singapore is an island state with a low average elevation above sea level, the loss of coastal land to flooding will be imminent [20,21].

Furthermore in recent years, Singapore has experienced an increased volume in rainfall which caused frequent flash floods during the monsoon seasons. For example, PUB [22] reports the number of days per year that experience a rainfall intensity of >70 mm in an hour increased at an average rate of 1.5 days per decade from 1980 to 2012.

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Fig. 3. Geographical location of the city of Singapore [23]

Results from past studies show that UHI phenomenon exists in Singapore. Nieuwolt [24] who was the first to conduct an urban climate study in Singapore found an UHIMAX of ~4.5ºC at 23:00 local time on a clear and calm night. However, this study was restricted to point measurements taken in the south of the island during a few nights in October which took place 48 years ago. The Meteorological Services of Singapore [25] conducted a study on a larger scale between 1979 and 1981. It reported similar findings to Nieuwolt [24], particularly identifying a nocturnal temperature distribution pattern for the whole island [25]. Chang [26] confirmed the existence of a nocturnal heat island phenomenon in Singapore and reported that the urban canyon geometry plays an important role in affecting the UHI. Also, Goh and Chang [26] found that the spatial extent of the UHI had increased as more undeveloped areas became urbanized. Both the Singapore Meteorological Service [27] and Goh and Chang [26] showed the existence of a large persistent warm belt covering the Central Business District (CBD), residential and industrial areas. Also, Chang [26] found that CBD was not more than 2.5ºC warmer than the rural areas in Singapore during the warm southwest monsoon months. Chow and Roth [18] discovered that the UHIMAX value for northeast monsoon season was not more than 6ºC at 21:00 local time.

While all these studies have yielded important results about the UHI phenomenon in Singapore, all studies are similar in a way - temperature collected in the "urban" site and the "rural" sites were taken to see the difference in results using the ΔTu–r approach. According to Oke [1], this traditional method lacks an accepted protocol to gather and report heat island observations in the canopy layer. Furthermore, given that Singapore has attained a 100% urban population index by the United Nations ESCAP [28] since 1980, it makes it even more unsuitable to use the conventional urban- rural approach in climate studies. Technically, "rural" does not apply into the vernacular of Singapore landscapes. Furthermore, as the LCZ framework has been newly developed in 2012 [1], there has not been any past climate studies that adopt this framework in examining the UHI studies of Singapore.

2. METHODOLOGY

2.1 Study Area

Singapore has undergone rapid changes in its physical landscape over the last 50 years. The amount of built-up area has almost doubled with a corresponding large decrease in farm area and forest spaces. Much of this urbanisation was associated with the construction of high-rise public housing estates across the island, which plays a significant role in Singapore's urban fabric.

Singapore has a total land area of 716.1km^2 [29]. Its land use has to cater to the demand of the current population of 5.4 million and a population density of 7540 people/km^2. This population is expected to increase to between 6.5 and 6.9 million by 2030 [30]. The city houses over 90% of its population in high rise public flats in 20 new towns spread across the island and in other smaller estates [29]. As of 2013, there are about 1.2 million housing units, of which 0.9 million are Housing Development Board (HDB) flats. This homogeneity helps to ensure that the observations are representative of the microclimate of the particular land use [31]. As of 2010, 14% of the land is allocated to housing, while 13% of the land is allocated to Industry and Commerce, 12% is land transportation infrastructure and 8% has been allocated to Parks and Nature Reserves [32].

In this study, three sites were assessed and monitored: i) an HDB (residential) site; ii) a park/green space site (CleanTech Park); and iii) a CBD site, Asia Square Tower 2 (Fig. 4). The selection of a "rural" site was challenging. Singapore has been classified a fully urbanized city since 1980 by the United Nations ESCAP [28]. Ideally, following the Lowry framework [18], the rural site should reflect pre-urban conditions and be unaffected by topographic or coastal influences, which would be the primary tropical rainforest for Singapore. However, the remaining primary rainforest is confined to a nature reserve in a small, hilly area in the centre of the island (Bukit Timah Nature Reserve) and hence is unsuitable. In Chow and Roth's study [18], the "rural site" consisted of a mix of secondary rainforest, agricultural land and military training grounds in the northwest of the island. Hence, in this work, the CleanTech Park that is built in a relatively less developed part of Singapore in the west was chosen for monitoring. The methodology adopted in this research followed the guidelines provided by Oke and Stewart [1] using a three-step process, outlined in the following sections.

2.2 LCZ Characterization

Step 1: Collect Site Metadata

Metadata refers to the state of the urban context around a particular measurement site [33]. According to Oke and Stewart [1], users must collect appropriate site metadata to quantify the surface properties of the source area for a temperature sensor. Fieldwork was performed to define the locations of the sites according to the LCZ framework. During the visits to these sites, necessary site metadata such as the local horizon, building geometry, land cover, surface wetness, surface relief, traffic flow, population density and photographs of the sites were taken. Photographs were taken using Sony's Nex 3 camera with a 16mm f/2.8 pancake wide angle lens. Secondary sources of site metadata which included aerial photographs, land cover/land use maps, and Google Earth images were used. According to Emmanual et al. [33], this step provides an understanding of the city in terms of its morphology and its influence. In this study, a detailed map of different districts of Singapore was generated using Google Map images to establish the urban block for LCZ definition. The maps include urban blocks and building outlines, roads, land contours (See Figs. 5-7).

Site metadata includes sky view factor which was obtained through the photographs taken when conducting field surveys. Aspect ratio, mean building or tree height, building surface fraction and impervious surface fraction which were obtained through field surveys, Google Earth, and satellite imagery. Terrain roughness class, surface admittance, albedo as well as anthropogenic heat flux were obtained using the LCZ data sheets as guide.

Fig. 4. Sample site locations

Fig. 5. Detailed map of selected Site 1, HDB Residential Estate (Google, 2014)

Fig. 6. Detailed map of selected Site 2, CleanTech Park

Fig. 7. Detailed map of selected Site 3, CBD

Step 2: Define the Thermal Source Area

The temperature (T), wind speed (u), and relative humidity of the three sample locations were measured using a Kestrel 4000 weather tracker and data collected were transferred using the Kestrel data logger. The Kestrel weather trackers were programmed to collect data at hourly intervals over a 5 day period in January 2014. Measurements were taken at a standard height of 2 metres above ground (see Fig. 8). Oke and Stewart [1] noted that the circle of influence is difficult to quantify but observational evidence suggested that a radius of 100 – 200 m was appropriate for screen height measurements. Using the trial version of Google Earth Pro, circles of influence of 200 m for all three sites were defined. The "circles of influence" of the 3 sites were first parameterized by the general properties of the local climate zones. Photographs alone can substantiate a reasonably accurate match between field site and local climate zones, but a direct relation between the measured parameters and the zone datasheets ultimately supports a more objective and reproducible outcome [34].

Fig. 8. Instrument mounted on a tree at screen height of 2m above ground at Clean Tech Park

Step 3: Select the Local Climate Zone

The most appropriate LCZ for each site was selected by matching the observed data with that of the selection guideline developed by Oke and Stewart [1].

The guidelines are broadly categorised according to (after Emmanuel et al. [33]):

1) Zone Definition – Physical characteristics that all zones in this class possess
2) Zone Illustration – Typical views of the built fabric portrayed using sketches and images
3) Zone Properties – Parameters that are deemed to drive the Urban Heat Island phenomenon.

LCZs represent spatially uniform surface cover, structure, material, and human activity that may be on the scale of hundreds of meters to several kilometres [35]. 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 [1]. As noted above, there can be up to 10 built types ranging from LCZ 1 to LCZ 10 and 7 land cover types ranging from LCZ A to LCZ G, and these types can have variable seasonal or shorter period land cover properties (See Table 1).

3. RESULTS

The mean air temperature for the 3 different sites over the course of 5 consecutive days is shown in Fig. 9. The completed LCZ assessment forms are shown in Figs. 9-11 are shown in Fig. 9.

Overall, the three selected sites appear to be well represented by the LCZs (Figs. 10-12). In other words, with minor exceptions the metadata for each site compared favourably with the general zone properties. The zone captured the ephemeral nature of the "rural" sites of Singapore, such that it is placed into separate classes for low plants conditions. Differences in built form are also captured by the zones, such that urban sizes are placed into separate classes for high and low building density.

The UHI intensity for each LCZ was calculated as:

$$\Delta T_{LCZ\ X-Y}$$

where the temperature (ΔT) is the maximum difference of LCZ X – Y., and X= LCZ temperature of the zone of interest and Y = LCZ temperature of the comparison zone.

Results for the UHI intensity calculations are shown in Table 2.

4. DISCUSSION

CleanTech Park, categorized as LCZ 9, had the lowest temperature compared to the other two sites. Throughout the 5 days of data collection, its mean air temperature was 25.69ºC. The greatest difference between the other two sites, LCZ 9 and 4, was 2.01ºC and the smallest difference was 0.79ºC, between LCZ 9 and 1. This finding coincides with Chang [26], who found that the CBD generally was not more than 2.5ºC warmer than the rural areas during the warm southwest monsoon months. Furthermore, Fig. 9 suggests the CBD tended to be warmer at night to early morning, particularly from midnight to 6 am. Oke [16] suggested that the ideal time to conduct the spatial surveys for UHI is a few hours after sunset or sunrise on nights with relatively calm airflow and cloudless skies. This maximizes the potential for the differentiation of micro- and local climate differences.

The HDB residential estate (LCZ 4) had a higher mean air temperature than the CBD District (Table 2) when the entire day is considered and based on a t-test, this difference was significant at α=0.05.

Several factors may help to explain the higher mean of LCZ 4. First, the LCZ 4 site is impacted by a HDB surface car park, a common feature found in older and matured HDB estates. Local vehicle activity could result in the direct heating of the environment [11]. A field survey was conducted on a separate day at the car park to observe the traffic movement of the vehicles. It was observed that the highest number of incoming vehicles that parked stationary in the parking lots were between 7pm and 9pm. The car park was fully occupied by 9.50pm. As engines of the vehicles take about 30 minutes to an hour to cool off completely, the heat emission may affect the air temperature. As parking lots are considered one of the hotspots in urban space, the anthropogenic heat may be one reason why the HDB site has higher air temperature compared to the CBD site.

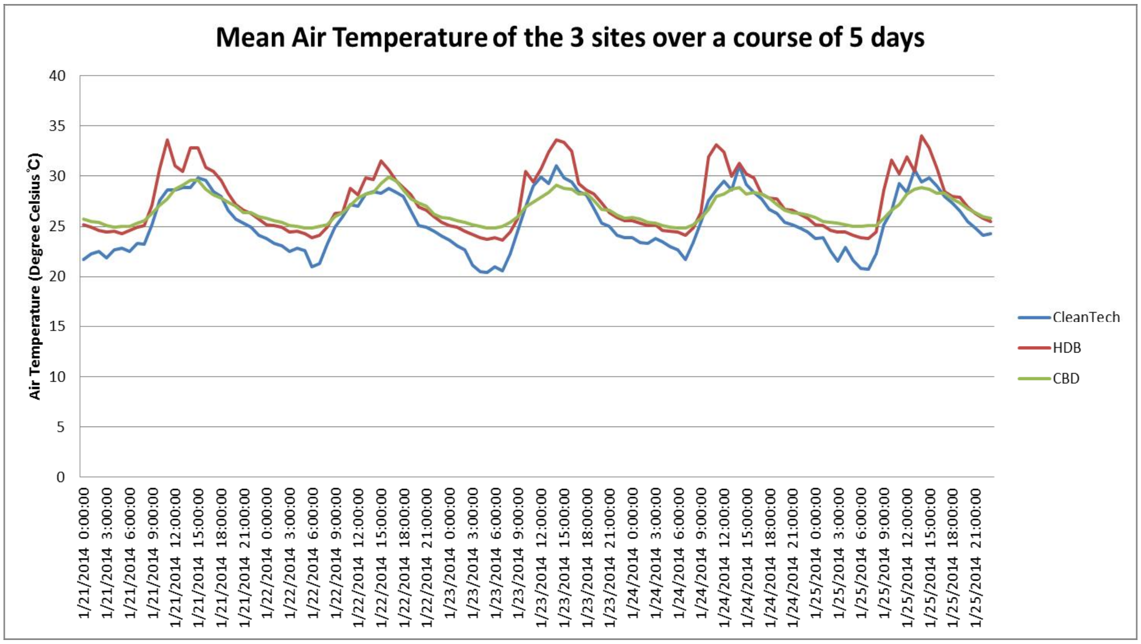


Fig. 9. Mean air temperature measured at 3 different sites over a course of 5 consecutive days

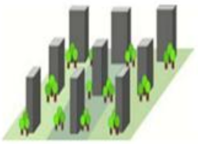
LCZ **Open High-Rise** **4**

Definition

Form: Open arrangement of tall buildings to tens of stories. Abundance of pervious landcover (low plants, scattered trees). Landcover: Concrete, steel, and glass construction materials accompanied with thick roofs and walls. Roofs typically flat. **Function:** HDB Residential Estate, Apartment Blocks, Highrise Housing Estates. **Location:** West

Illustration

High Angle



Low Angle

PROPERTIES

Sky view factor	0.5 – 0.7
Canyon aspect ratio	0.75 – 1.25
Mean building height	> 25 m
Terrain roughness class	7 – 8
Building surface fraction	20 – 40 %
Impervious surface fraction	30 – 40 %
Pervious surface fraction	30 – 40 %
Surface admittance	1,100 – 2,000 J m^{-2} s$^{1/2}$ K^{-1}
Surface albedo	0.12 – 0.25
Anthropogenic heat flux	< 50 W m^{-2}

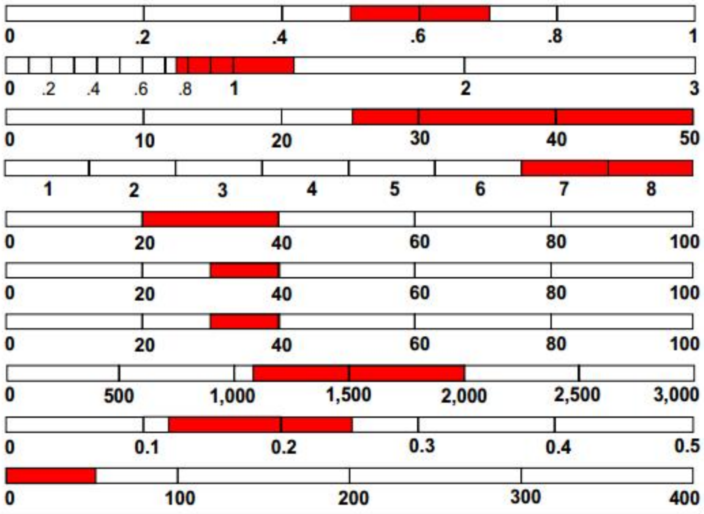
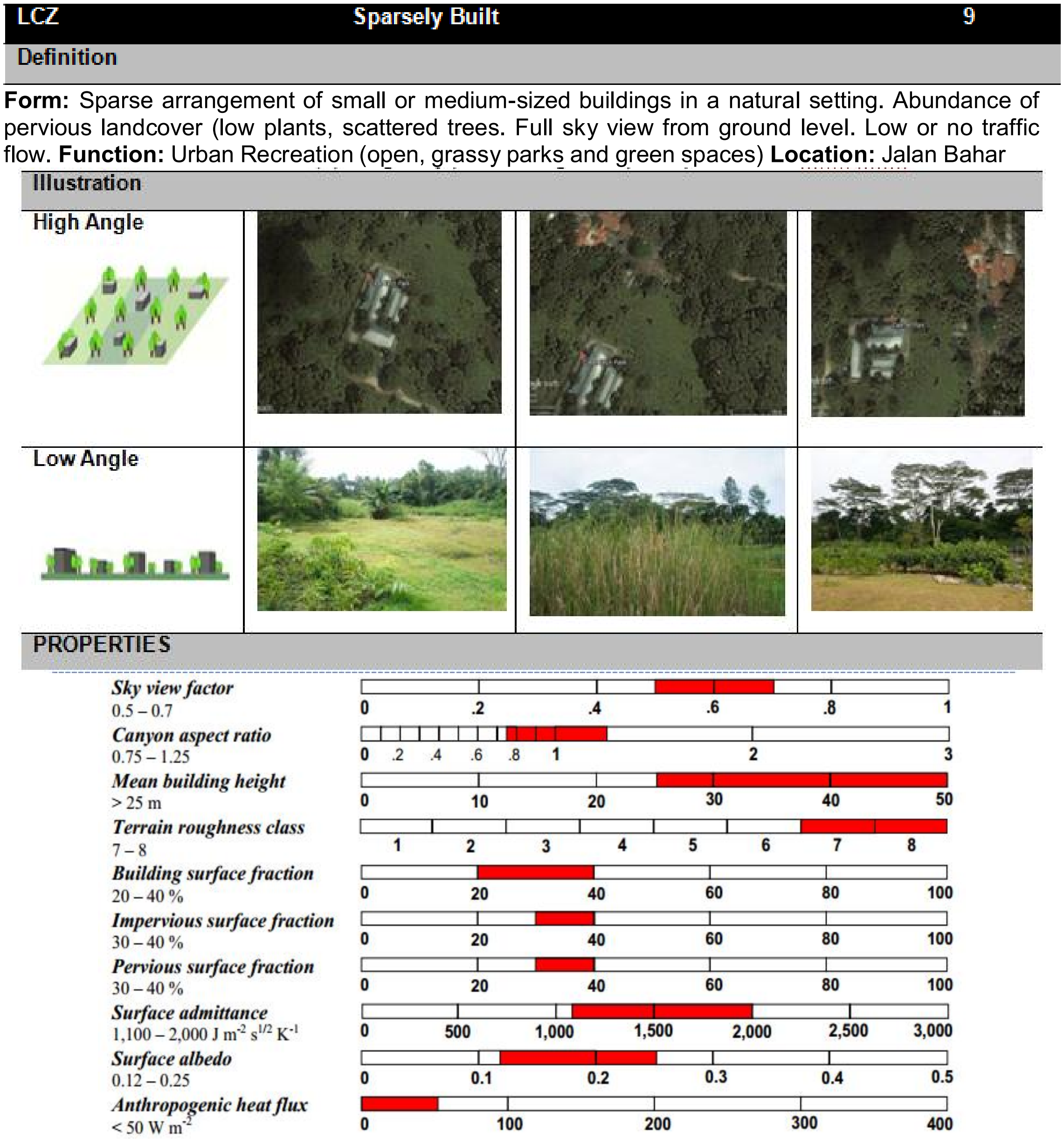


Fig. 10. Local climate zones datasheet of site 1, HDB



LCZ **Sparsely Built** **9**

Definition

Form: Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious landcover (low plants, scattered trees. Full sky view from ground level. Low or no traffic flow. **Function:** Urban Recreation (open, grassy parks and green spaces) **Location:** Jalan Bahar

Illustration

Fig. 11. Local climate zones datasheet of site 2, CleanTech Park

Another possible reason for the lower air temperature attained for the CBD area is that the Asia Square Tower 2, is an example of office building designed to be green [36]. This green building is a common feature in Singapore building stock. According to BCA [37], Singapore is “the most heavily involved in the development of green buildings today” and office buildings comprise a significant percentage of the building stock in Singapore. As of today, there are 1696 green mark building projects in Singapore [37]. Green designs reduce energy use and heat adsorption at their surface [38]. For example, Asia Square Tower 2 uses integrated heatpipes designed for efficient dehumidification and temperature control [39]. As seen in Figs. 10-12, there also are more trees planted along the pavement at the CBD site compared to the HDB residential area. This shows the importance of green space which can help to reduce the temperature of built-up areas [40].

LCZ **Compact High** **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. Buildings of Steel, concrete, and glass construction materials. Landcover mostly paved. Few trees. Heavy traffic flow. **Function:** Commercial (office buildings) **Location:** Core Central Business District.

Illustration

PROPERTIES

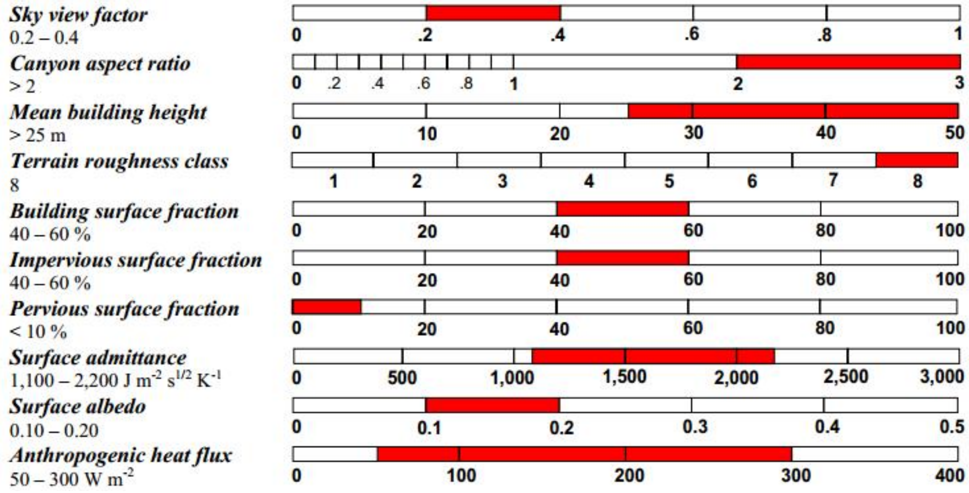


Fig. 12. Local climate zones datasheet of site 3, CBD

Another plausible reason for the lower air temperature attained in CBD area is because of its human activities at night. As seen in Fig. 9, it is noticed that the air temperature attained in the CBD after office hours (6pm – 8pm) is generally lower than the air temperature attained in the HDB residential estate. This could be attributed to the factor whereby increased human activities start to take place in the HDB residential estate and decrease in the CBD area, when people return back home after work (again, observed at the HDB parking lot).

Table 2. Urban Heat Island Intensity (UHI) of LCZs

Site	Mean air temperature (°C)	Local climate zone		Urban Heat Island using the mean air temperature difference of LCZ ($\Delta T_{\mathrm{LCZ\ X-Y}}$) (°C)
		Zone #	Zone title	
1. HDB Residential Estate	27.70	4	Open high-rise	$\Delta T_{\mathrm{LCZ}\ 4-9} = 2.01$ $\Delta T_{\mathrm{LCZ}\ 4-1} = 1.22$
2. CleanTech Park	25.69	9	Sparsely built	$\Delta T_{\mathrm{LCZ}\ 9-4} = -2.01$ $\Delta T_{\mathrm{LCZ}\ 9-1} = -0.79$
3. CBD District	26.48	1	Compact high-rise	$\Delta T_{\mathrm{LCZ}\ 1-9} = 0.79$ $\Delta T_{\mathrm{LCZ}\ 1-4} = -1.22$

4.1 UHI and Urban Design

With the application of the LCZ system, the process of substantiating cross-study differences in urban heat island (UHI) magnitude is more useful. UHI magnitude is expressed more objectively through “inter-zone” temperature differences than through arbitrary “urban-rural” differences [34]. Heat islands defined this way become more robust indicators of city climate medication than those defined by the urban-rural calculation. This would aid greatly during the standardization of the calculation of a Liveable City Index, in particularly, the aspect of Urban Heat Island Effect.

In order to maintain its standard as the top liveable city in the ASEAN region, the land use planners in Singapore are striving to improve living conditions to keep its standard high while coping with the increasing population. According to Vanessa Timmer and Nola-Kate Seymoar [41], a liveable city must be a sustainable city. Using the same logic, Evans [6] compares “liveability” to a coin with two faces – livelihood and ecological sustainability. Similarly in Singapore, the Centre for Liveable Cities [42] adopts the CLC liveability frame work which considers a competitive economy, sustainable environment, and high quality of life [42].

A key strategy is to promote sensitive urban development that preserves open space and ecological integrity of land and water, that is, a balance of city and country [43]. These qualities may be achieved through a wide variety of means including urban consolidation, various methods to reduce traffic and urban heat island effect, encourage greater use of renewable energy, green roofs and public transport, a holistic approach to nature, history, heritage, health and safety, and a life cycle approach to energy, resources and wastes [44].

As of 2013, there are about 1.2 million housing units in Singapore, of which 0.9 million are HDB flats [29]. To support the projected 2030 population range, 1.9 million homes will be developed [32]. This figure is an increase of 700,000 housing units from today. It is envisioned that higher density buildings will be built to optimize land use in order to cater to the housing demand. Hence, it is very likely that more LCZ 4 and lower will be the dominant LCZs of the city. It is expected that there will be development of some of the reserve land and land with lower intensity will be recycled to achieve higher land productivity. This means that the number of LCZ 8 areas and above will decrease and that the UHI in the future could be higher than the current situation. It is timely now to examine how the green infrastructure is being developed and how the energy consumption of individual buildings is being reduced to mitigate such problems.

Apart from the newly developed buildings, mature housing estates which play a significant role of Singapore’s urban fabric are also in need of urgent rejuvenation and retrofitting to adapt to climate change [45]. There is a need to rethink and reconceptualise these mature estates, which are over 3 decades old in order to future proof them for a more sustainable city. System-integration and holistic conceptual approaches are necessary to ensure that these rejuvenated estates become part of a larger ecosystem [45]. Alternatively, the Skyrise Greenery scheme should be further expanded to make more high-rise buildings or more infrastructures such as bus-stops and link bridges to have a green roof installed so as to ensure sustainable living conditions in the long-term [46,47,48].

4.2 Integrating Remote Sensing in Future Studies

Remote sensing technology is another approach that has been employed to investigate the UHI effect [49,50,51,52,53]. Oke and Voogt [54] and Mirzaei and Haghighat [55] reviewed some of the challenges in applying this technology, including the inability to capture the three dimensional or vertical domain of energy exchange in urban canyons, issues of converting surface UHI to an atmospheric UHI, time limitations on the field of view, and atmospheric interference due to cloud cover. This latter issue is of particular concern in Singapore where, on average, it rains every second day. Nonetheless, the technology is maturing to the extent that it is now becoming possible to cost-effectively track long term trends in UHI characteristics and even make connections to urban storm events [53]. Furthermore, through the remote sensing approach there is the advantage of more readily visualizing the spatial extent of the UHI effect. An interesting area for future research would be to integrate the LCZ approach with remote sensing. This type of integrated approach would both help to ground truth imagery signals for more detailed data interpretation and also could help to direct where to conduct specific LCZ studies within a city.

5. CONCLUSION

Urban heat island can be observed in the growing cities throughout the world. The difference in air temperature between the urban and rural site (ΔT_{u-r}) has been the most commonly adopted method used to characterize UHI, until the new framework of LCZ was developed that allows a more meaningful and objective assessment.

The LCZ system offers an improvement to the study of urban tropical climatology. The classification of urban climate field sites is relatively unambiguous provided that the system that is being used is appropriately defined and scaled. With the standardized format used in classifying the LCZ, the properties that influenced the local climate are more distinct and clear. Also, because of its standardized definition of UHI magnitude, it enables valid comparisons with mid-latitude cities [1]. As this is only a small-scale study that acts as preliminary research, it would be useful if future tests using field data from different urban and rural environments can be demonstrated with a more advanced urban canopy models.

Overall, the use of LCZ in quantifying the UHI magnitude of Singapore is relatively straightforward given that the LCZ data sheets are provided as a set of standardized guidelines. As Singapore climate has no seasonal variation (summer all year long), it makes it a lot easier to fit them into the best fit properties, rather than cities with ephemeral landscapes that require a combination of LCZ classes and properties. It is definitely much easier to adopt this method rather than the traditional rural-urban classification as Singapore can be difficult to find the best fit “rural” area as it is highly urbanized.

The three defined LCZ types in this study were: LCZ 1, 4 and 9. Results and analysis revealed the importance of green spaces (LCZ 9) which had a relatively lower air temperature compared to the other two LCZs. The greatest temperature difference between zones was observed for LCZ 4 and LCZ 9 at ~2.01ºC. While the need to transform and repurpose land of lower intensity to meet the demand of growing population may be inevitable, it is recommended that the development of these areas be limited to large low rise, such as schools, green parks. The findings serve as an important reminder to the city planners in Singapore not to compromise on green spaces for the sake of more built up spaces. Otherwise, it is expected that the excess heat present in the city would affect the comfort, health and performance of the inhabitants. The challenge for future research is to see how to meet the demands of the future needs of Singapore, while adapting and mitigating the negative effects of such development so as to achieve a sustainable development.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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