Classifying Thermal Climate Zones to Support Urban Environmental Planning and Management in the Bangkok Metropolitan Area
การจำแนกเขตภูมิอากาศความร้อนเพื่อสนับสนุนการวางแผนและจัดการสิ่งแวดล้อมเมืองในพื้นที่กรุงเทพมหานคร

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Abstract

The Thermal Climate Zone (TCZ) is the basic unit of urban planning, defined as an area of thermally homogenous surface structure and cover, which was used in a GIS-multivariate analysis approach to delineate thermal climate units. With an understanding of the thermal impacts that planning decisions can have, it is essential to know how TCZs can be designed to regulate temperatures in the urban environment. Our aim in this study was twofold: 1) to facilitate consistent documentation of zone 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 the city. The analysis presented was applied on Bangkok Metropolitan Area. By surface properties differentiation, the urban-rural continuum yields a hierarchy of 7 TCZs. Land surface temperature was extracted from daytime LANDSAT TM (April 25th, 2009) image which was used to represent the stability of summer temperatures for different TCZs. We found that an urban–rural temperature difference, or urban heat island intensity, can often exceed 4.23°C in the summer. A spatially exhaustive map of TCZ would be helpful for city planners for two reasons. First, it would localize urban areas concerned by different climate behavior over the summer season and represented as a good indicator of urban climate variability. Second, when overlaid with a land cover map, this TCZ map may contribute to the identification of possible urban management strategies to reduce heat wave effects in the city. These results are clearly useful and essential pieces of information that can be applied in urban planning to improve climate adaptability.

บทคัดย่อ

เขตภูมิอากาศความร้อน เป็นหน่วยเชิงพื้นที่พื้นฐานของการวางแผนเมืองที่กำหนดจากบริเวณสิ่งก่อสร้างและสิ่งปกคลุมพื้นผิวซึ่งมีลักษณะเหมือนกันจากการจำแนกด้วยความร้อนโดยใช้วิธีการวิเคราะห์ตัวแปรหลายตัวด้วยระบบสารสนเทศภูมิศาสตร์เพื่อจำแนกหน่วยภูมิอากาศความร้อน ผลกระทบที่เกิดจากความร้อนดังกล่าว จึงมีความสำคัญต่อการวางแผนเชิงพื้นที่ซึ่งจะทำให้ทราบถึงแนวทางการออกแบบและวางแผนในแต่ละเขตภูมิอากาศความร้อนเพื่อควบคุมอุณหภูมิ

ในสภาพแวดล้อมเมือง วัตถุประสงค์ในการศึกษานี้แบ่งเป็นสองด้าน ได้แก่ 1) เพื่อให้การอธิบายข้อมูลลักษณะของเขตภูมิอากาศความร้อนที่สอดคล้องกันและปรับปรุงเกณฑ์ในการเปรียบเทียบระหว่างเขตภูมิอากาศความร้อน และ 2) สร้างเกณฑ์การวัดขนาดความรุนแรงของผลกระทบเกาะความร้อนในพื้นที่เมือง ซึ่งกำหนดให้กรุงเทพมหานครเป็นเขตพื้นที่ศึกษาในครั้งนี้ โดยพบคุณสมบัติของพื้นผิวที่แตกต่างกันถึง 7 เขตภูมิอากาศความร้อน ตั้งแต่เขตเมืองต่อเนื่องไปยังเขตชนบท และได้ทำการประเมินอุณหภูมิพื้นผิวที่ได้จากข้อมูลภาพถ่ายช่วงเวลากลางวันของดาวเทียมแลนด์แซท ทีเอ็ม (ณ วันที่ 25 เมษายน ค.ศ. 2009) ซึ่งถูกนำมาใช้ทดสอบความเสถียรของอุณหภูมิช่วงฤดูร้อนในเขตภูมิอากาศความร้อนที่ต่างกัน โดยพบว่า ความแตกต่างของอุณหภูมิในเขตเมืองและเขตชนบท หรือความรุนแรงของปรากฏการณ์เกาะความร้อนเมืองนั้น สูงถึง 4.23 องศาเซลเซียส ในช่วงฤดูร้อนด้วยแผนที่แสดงข้อมูลเชิงพื้นที่ของเขตภูมิอากาศความร้อนนี้จะเป็นประโยชน์สำหรับนักวางแผนเมือง ด้วยเหตุผลสองประการ คือ ประการแรกแผนที่จะระบุบริเวณพื้นที่เมืองที่วิกฤติจากสภาพภูมิอากาศแตกต่างกันในช่วงฤดูร้อน และเป็นตัวบ่งชี้ถึงความแปรปรวนของสภาพภูมิอากาศในเมือง และประการที่สอง เมื่อนำแผนที่สิ่งปกคลุมดินมาซ้อนทับ แผนที่นี้จะมีส่วนสนับสนุนการกำหนดกลยุทธ์การจัดการเมืองที่เป็นไปได้เพื่อลดผลกระทบจากคลื่นความร้อนในเมือง ซึ่งจะเป็นประโยชน์และเป็นข้อมูลสำคัญในการวางแผนเมืองเพื่อปรับปรุงสภาพภูมิอากาศให้ดีขึ้น

Keywords (คำสำคัญ)

Thermal Climate Zone: TCZ (เขตภูมิอากาศความร้อน)
Urban Heat Island: UHI (เกาะความร้อนเมือง)
Land Surface Temperature: LST (อุณหภูมิพื้นผิว)
GIS and Remote Sensing (ระบบสารสนเทศภูมิศาสตร์และการสำรวจจากระยะไกล)
Urban Environmental Planning and Management (การวางแผนและจัดการสิ่งแวดล้อมเมือง)

1. Introduction

Facing the concern of the population to its environment and to climatic change, city planners are now considering the urban climate in their choices of planning. Yet the urban climate of tropical cities remains a subject insufficiently studied (Oke, 1984, pp. 1-10). This concern becomes even more important in the case of tropical cities, because spatial dynamics come with environmental alterations. In a hot and humid climate, increases in urban temperature expose inhabitants to difficult thermal conditions. One of best known effects is the Urban Heat Island (UHI) refer to areas within the city, where the canopy and boundary air layer temperature or the surface temperatures are higher than those of rural surroundings (Wong & Chen, 2005, pp. 547-558). The temperature increase is not regular, but depends heavily on urban morphology; seem to be the main characteristics of urban climate. The difference between urban and rural temperature is called Urban Heat Island Intensity (UHII). Thus, urban climatic information will continue to be necessary.

Furthermore, the integration of urban climate knowledge with city planning has not been successful, in part because urban climatology has advanced slowly around issues of scale and communication (Mill, 2006, pp. 69-79). In such conditions, the use of climatic maps such urban climate zones could advance these issues because it offers a basic information of urban climate principles for architects, planners, ecologists, and engineers (Houet & Pigeon, 2011, pp. 2180-2192; Oke, 1984, pp. 1-10). For different purposes, scientists have developed landscape classification adapted to urban areas and oriented for climate studies. Urban climate maps can be considered as the first spatially exhaustive and expert-knowledge approach to provide information and planning recommendations that integrate climate factors (Ren et al., 2011, pp. 2213-2233). This method combines geographic terrain information, land surface maps and analytical climate maps to provide urban climate maps under user defined scenarios. Such studies were improved by integrating urban morphology (building volume, green coverage ratio, etc.) (Ng, 2009). Others urban climate classifications were defined to highlight urban influence on local climate: Urban Terrain Zones (Ellefsen, 1990/1, pp. 1025-1049); Urban Climate Zones (Oke, 2004); Local Climate Zones (Stewart & Oke, 2012, pp. 1879-1900). These classifications show some limitations: First, urban climate identification and derived classifications systems still require an expert-based approach, Second, temperature differences between zone climates have not been yet quantified.

Moreover, the interest of these classifications comes from their independence to specific climate conditions especially should extend to Asia cities, which rapid urbanization mainly took place in most developing countries (Figure 1a). Given this trend, the urban thermal environment has become a global phenomenon as cities attempt to accommodate increasing demand for housing, commercial development, recreation space, and other uses which in turn increases the energy consumption of buildings, alters urban climatology, modifies urban wind patterns, and increases the concentration of air pollutants. Particularly, several large Asian cities are all rapidly developing and show various developmental stages of temperature has increased by approximately 2.5°C during the 20th century (Figure 1b) (Kataoka et al., 2009, pp. 3112-3119). These cities phenomenon has far-reaching environmental sustainability and human livability implications ranging from the aggravation of health problems, increasing the intensity of urban air pollution, and contributing to extreme heat waves. As a result, an occurrence of urban environmental problems is inevitable. In this respect, the urban thermal environment is one of the major urban environmental issues, which has led to extensive research into this topic.

In this study, we will look into areas in a band of latitudes 10° to 15° north and south of the equator,

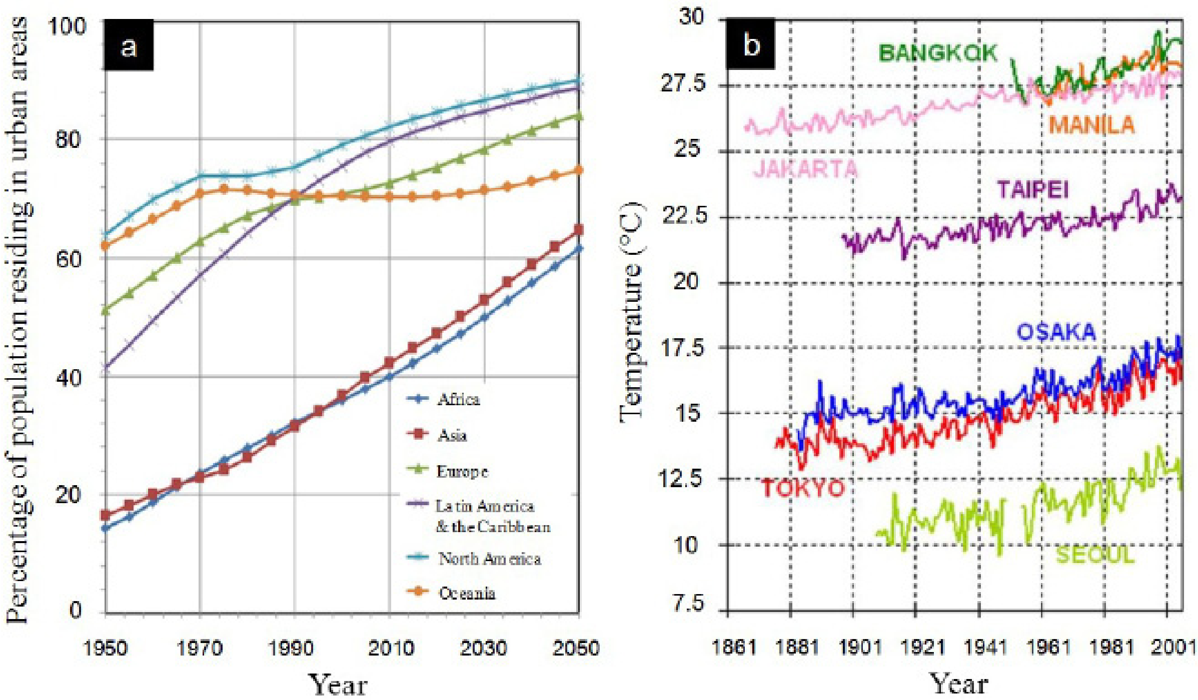


Figure 1. (a) Percentage of population residing in urban areas by continent 1950-2050 (UN, 2010) and (b) Variation in yearly mean temperature in large Asian cities using observational temperature data (modified from Kataoka et al., 2009).

also called "tropical climates" in the Southeast Asia especially a rapidly urbanization of the Bangkok Metropolitan Area (BMA), Thailand (UN, 2002; Kraas, 2007, pp. 9-22; Srivanit & Hokao, 2012, pp. 234-256). As a consequence there is now a growing community of Thai's scholars focused on urban climate. During the summer, it is usually between March to June, the highest mean monthly of solar radiation in BMA was only exceeded in April. These large values of the average solar radiation and its seasonal variations directly affect the amount and seasonal variations of the heat trapped by urban surfaces (Figure 2). As a result of such variation, the Surface Urban Heat Island (SUHI) is typically largest in the summer diurnal range (Golay, 1996, pp. 455-465); it could affect a city's environment and quality of life. The problem can be more complicated to solve and much research is still needed in this area with hot and humid seasons.

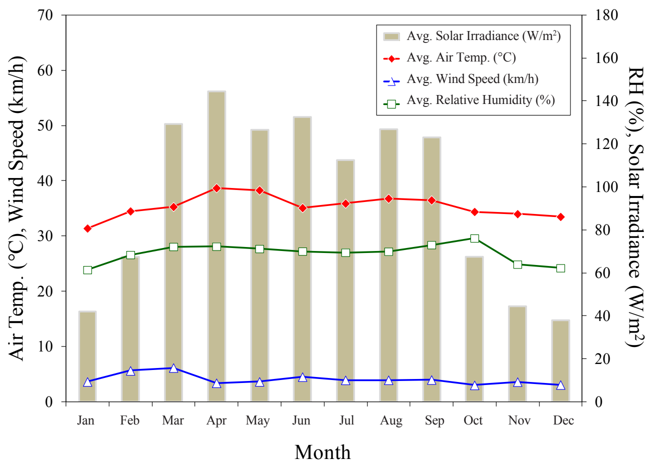


Figure 2. The monthly mean urban climatic variations during a 5-year period (from 2006 to 2010) for Bangkok (the reference station is located at 13° 44' 27.5994" N Latitude, 100° 32' 52.7634" E Longitude).

2. Methodology

2.1 Derivation of Surface Morphological Parameters

The technical flow employed in this research is presented in Figure 3. A geo-referenced building morphological dataset and detailed land use/land cover information in the area of interest were analyzed by using a Geographic Information System (GIS), which was made available in digital format by the Government of Bangkok Metropolitan Administrative. The building footprints were extracted from aerial photographs that were taken in 2009, and the number of floors in each building was manually counted. Each story was assumed to be 3 m. tall. Remote sending data is well suited to gain information of the green area on the surface. Above all, Normalized Difference Vegetation Index (NDVI) calculated from multispectral remote sensing data (LANDSAT TM data) is the most widely used vegetation index (Floyd, 1996, pp. 405-406). The method using NDVI have been proposed to estimate Green Coverage Ratio (GCR) and additionally the process of this method is simple (Purevdorj et al., 1998, pp. 3519-3535; Hirano, 2001, pp. 517-572; Sotoma et al., 2003, pp. 25-34).

In this study, the variables describing the surface morphology (surface configuration and composition) that were calculated include; *(i) Building Coverage Ratio (BCR)* is fraction of impervious surface cover and the density of urban construction materials (e.g. built-up, paved, asphalt) and affects local climate through modifies the albedo, moisture availability, and heating/cooling potential of the ground. The mean BCR at ground level were calculated to be 13.04%, with a standard deviation of 14.79%, and a range of 0.003% to 90.43%, except non-building grids. The results were found that the high-computed value area is located within the conglomeration of red grid cells (range from 60%-100%) that related within the BMA's downtown core area boundary such as Yaowarat District, is a historic core and old CBD which property has been owned by the oldest Chinese migrant families in BMA (also called the Chinatown of

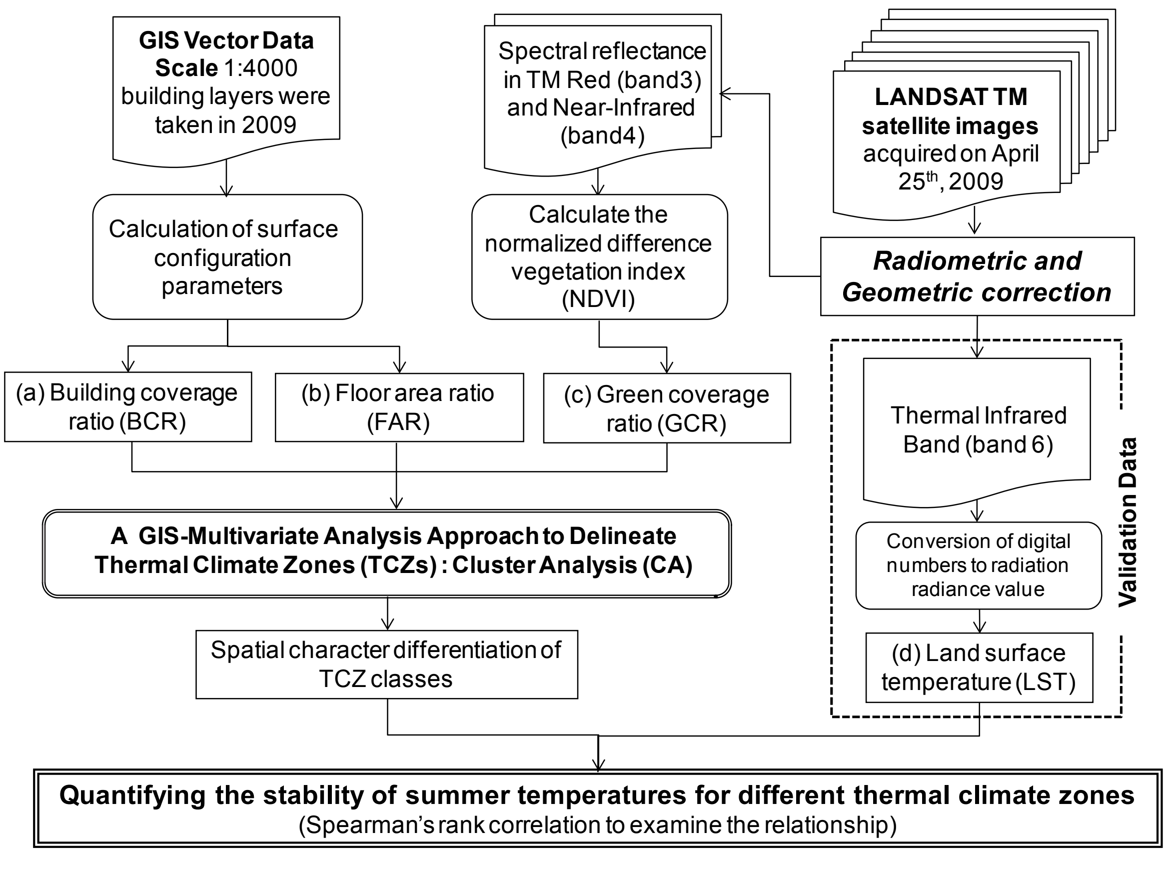


Figure 3. Technical flowchart of thermal climate zones classification and temperature stability evaluation.

Bangkok), as the business district gradually moved northwards to what is now known as the CBD area, the building was converted into a biggest retail and wholesale trading center (Figure 4a).; *(ii) Floor Area Ratio (FAR)* is a terms for planners used as a measure of the vertical intensity of the site being developed, a measure of the buildings floor area per unit horizontal area which significantly related to the surface roughness. The mean FAR was calculated to be 0.311, and the standard deviation was calculated to be 0.498 (range from 0.001 (a minimum value) to 6.963 (a maximum value)), except non-building grid contains approximately 434 grids of BMA (~7%). The distribution is unimodal, with more than 72% (4,790 grids) of the FAR in less than 0.5 range which is expanded in suburban to rural areas surrounding of the city-core area and associated with the agriculture area is clearly shown. Moreover, there are 52 grids (~0.8%) with the FAR greater than 2.5 (range from 2.5-7.0) (Figure 4b). The relatively high amount of FAR in the city is displayed by the distribution of red in a part of the figure. The results indicate that in inner BMA areas of the densely built, high-rise building areas such as Silom District (central business district) and expanded along the major transportation corridors (e.g. Sukhumvit Rd., Phaya Thai Rd., Ratchaprarop Rd., etc.). This area filled with banking institutions, corporate high-rises and condominiums with large building footprints had higher building aspect fraction values than other suburb areas.; and *(iii) Green Coverage Ratio (GCR)* is a fraction of green cover (e.g. trees, grass, shrubs, bush, and cultivated plants) and the density of pervious surface cover (e.g. bare soils, sand), that can help to increase infiltration and affect local climate through modifies lower surface and air temperatures by providing shade and through evapotranspiration of the pedestrian level, which are most important basic urban planning metrics significantly affects local climate (Golany, 1996, pp. 455-465; Grimmond & Oke, 1998, pp. 1262-1292; Srivanit & Hokao, 2011, pp. 34-46; Zhao et al., 2011, pp. 1174-1183; Hu & Yoshie, 2013, pp. 39-51). It was found that the mean GCR was computed to be 46.29%, with a standard deviation of 28.12%, and a range of 0.25% to 100%, mostly high GCR located in the eastern part of BMA corresponded to a heavy cultivation planted region, but a relatively small amount of park space (e.g. urban park, neighborhood playgrounds and gardens, etc.). The vast majority of this agricultural area is actual farmland and the balance shrimp farms on the periphery of the contiguous city boundaries (Figure 4c). These parameters were calculated for the entire on spatial grid cells with a size of about 300 m., which overlaid with 6,620 uniform grid cells. The surface morphological data was integrated to every grid mesh mapped. Additional validation data was obtained from thematic cartography of the mean surface temperature, which derived from thermal infrared remote sensing of LANDSAT TM image that acquired on April 25th, 2009 (Srivanit & Hokao, 2012, pp. 83-100) (Figure 4d). This information was used to verify the stability of summer temperatures for different climate zones. Hereafter, all grids to emerge from logical division of the surface morphological universe are called *"Thermal Climate Zones"* or *"TCZs"*.

2.2 A GIS-Multivariate Analysis Approach to Delineate Thermal Climate Zones

Usage of GIS has become a powerful tool to evaluate the urban thermal environment of a given region because it permits the fast integration and representation of several surface morphological attributes. The main goal of this task is to produce an *Urban Thermal Environmental Map (UTEMap)* using multivariate analysis approach that was applied relatively to local temperature studies using thermal infrared remote sensing observations. Identification of potential thermal sources or processes may be carried out by means of multivariate statistical analyses of surface morphological data sets from urban to rural areas. Moreover, the combination of multivariate

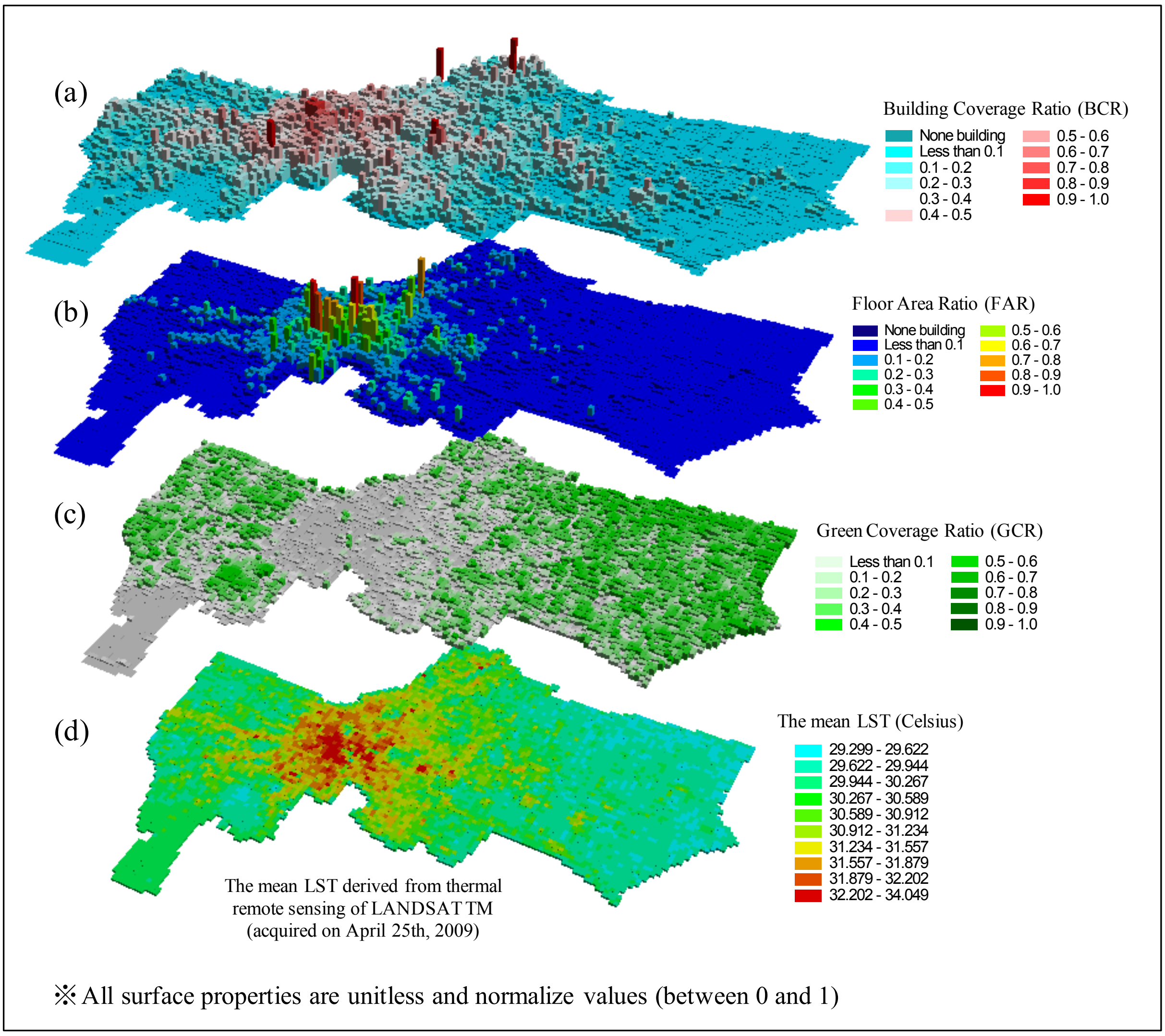


Figure 4. The spatial patterns of surface morphological variables [(a) to (c)] and (d) variation of land surface temperature in the summer.

statistical techniques with a geostatistical approach such as *Cluster Analysis (CA)*, was contributed to identify the impact point of resolved sources/ processes. In the study, CA is used to partition the data set into a number of data subsets with similar characteristics. It was also used as a prior step to cluster observations in order to extract more stable data subsets to be used as input to subsequent multivariate analysis. CA was used to perform initially to group locations that show similar behavior in terms of range of concentrations in order to obtain approximately surface homogeneous subgroups of TCZs. We did CA by running the K-Means in SPSS statistics software to assess the reasonable hierarchical clusters.

The vector of attribute values for any particular climate zone will have some degree of similarity with all seven TCZ class centroid properties, and therefore have some degree of membership to each of the seven TCZ classes. To estimate the degree of membership of each pixel in each of the seven urban classes, the Euclidean distance (d_E) between the pixel attribute vector, x, and that of each urban class mean (μ_c; Table 1) was calculated using Equation [1]:

$$d_E(x,\mu_c)=\sqrt{\sum_{j=1}^{n}(x_j-\mu_{cj})^2} \quad [1]$$

Where $d_E(x,\mu_c)$ is the "distance" between zone x and the class centroid μ_c for class c, $(x_j-\mu_c)$ is the distance between zone and class centroid for attribute j, and n is the number of attributes (see Table 2, Figure 5 and Figure 6). This measures the similarity between the zone vectors of attribute values, and the class vector of centriod attribute values (Ahamed et al., 2000, pp. 75-95; Owen et al., 2006, pp. 311-321). The "distance" values $[d_E(x,\mu_c)]$ were used to calculate a vector of fuzzy class membership grades for each zone using:

$$f_c(x)=\frac{\frac{1}{d_E(x,\mu_c)}}{\sum_{i=1}^{m}\frac{1}{d_E(x,\mu_i)}} \quad [2]$$

Where $f_c(x)$ is the membership grade of zone "x" in class "c" with values between 0 and 1, $d_E(x,\mu_c)$ are calculated in Equation [2], and m is the number of urban-rural classes (Ahamed et al., 2000, pp. 75-95). In this analysis, there are seven TCZ classes (i.e. $m=7$), so a membership-grade vector of seven values is calculated for each zone (Table 3). By definition, the sum of all membership values in a zone's membership vector is 1.

Table 1. Mean class centroid (μ_c) of three surface properties in each of seven TCZ classes

Attributes[a] (Unitless)	Class 1 3,794[b]	Class 2 1,305[b]	Class 3 871[b]	Class 4 483[b]	Class 5 91[b]	Class 6 63[b]	Class 7 13[b]
FAR	0.007	0.008	0.017	0.064	0.120	0.206	0.553
BCR	0.032	0.033	0.072	0.237	0.376	0.559	0.527
GCR	0.814	0.118	0.528	0.326	0.135	0.051	0.082

[a] All properties are standardized (normalized) value [unitless]

[b] Total climate zones

Table 2. Distance between mean class centriod (μ_c) for each classes

Class	1	2	3	4	5	6	7
1		0.376	0.760	1.149	1.658	1.335	2.092
2	0.376		0.385	0.774	1.287	1.004	1.815
3	0.760	0.385		0.390	0.907	0.693	1.553
4	1.149	0.774	0.390		0.521	0.484	1.335
5	1.658	1.287	0.907	0.521		0.549	1.104
6	1.335	1.004	0.693	0.484	0.549		0.870
7	2.092	1.815	1.553	1.335	1.104	0.870	

Table 3. Summary of the mean class membership vectors

Membership of class			FAR [a]		BCR [a]		GCR [a]	
			Mean	Std.	Mean	Std.	Mean	Std.
Class	1	3,794	0.007	0.008	0.030	0.032	0.598	0.262
	2	1,305	0.045	0.018	0.177	0.045	0.416	0.166
	3	871	0.095	0.032	0.324	0.043	0.226	0.115
	4	483	0.152	0.040	0.475	0.051	0.098	0.069
	5	91	0.263	0.074	0.664	0.093	0.031	0.053
	6	63	0.365	0.088	0.457	0.076	0.100	0.073
	7	13	0.735	0.146	0.553	0.095	0.078	0.055
Total		6,620	0.045	0.071	0.144	0.163	0.463	0.281

[a] All properties are standardized (normalized) value [unitless]

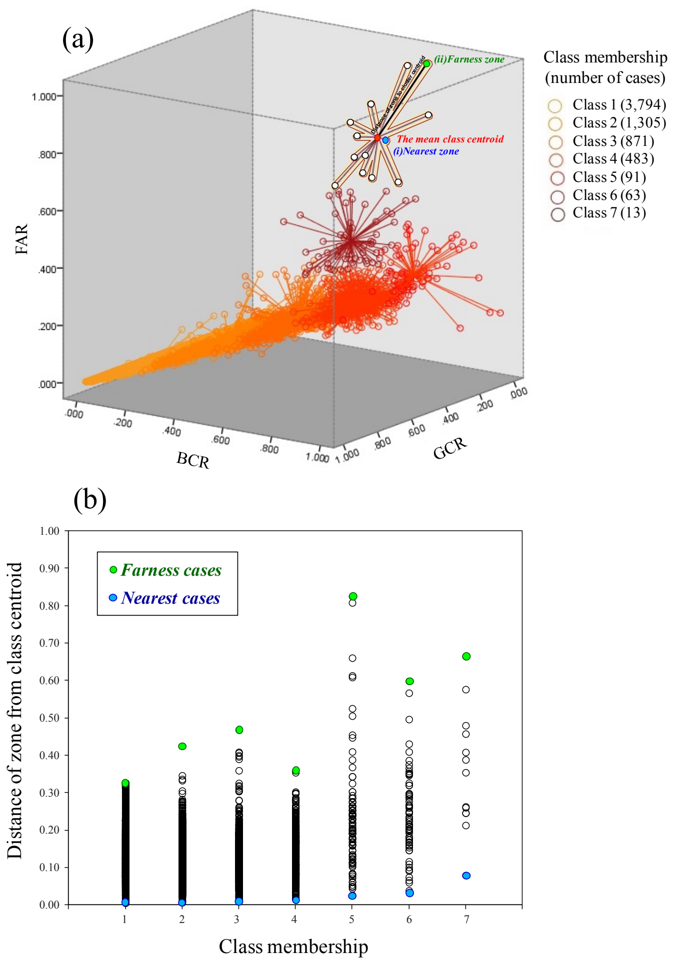


Figure 5. (a) 3D Scatterplot of different attributes combination, and (b) distance between zone and class centroid for each class ($n = 6{,}620$).

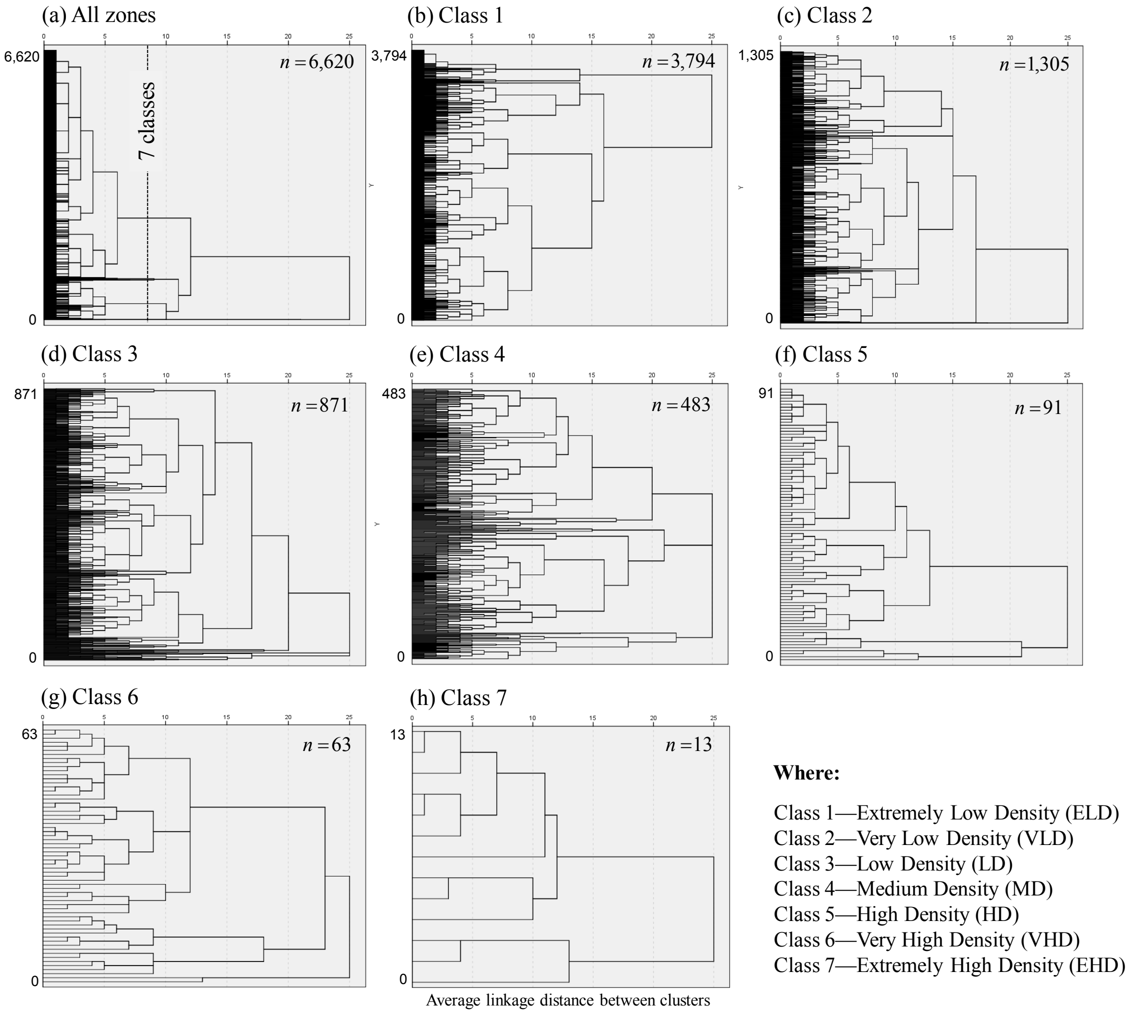


Figure 6. Tree graphs obtained from the cluster analysis (CA) and plotted on Euclidean Distance for; (a) All zones, (b) Class 1, (c) Class 2, (d) Class 3, (e) Class 4, (f) Class 5, (g) Class 6 and (h) Class 7.

Ordinary significance tests, such as analysis of variance *F*-tests, are valid for testing differences between clusters. The results of clustering was attempted to maximize the separation between clusters and the assumptions of the usual significance tests are not drastically violated. These are explored in ANOVA Table which offers *F*-values and significance levels (*p*-value) to show whether any of these mean differences are significant. The good result appeared obviously in 7 clusters. It can be seen in Table 4 that *F*-values for all the variables are significant at 5% level as their corresponding *p*-values are less than 0.05. The groups means are all significant, indicating each of the three variables reliably distinguish between the seven clusters.

3. Results

3.1 Spatial Character Differentiation of Thermal Climate Zone Classes

Cluster analysis was then used to generate the classes, and class centroids were found by calculating the class centroid of each of the three morphological attributes in each TCZ class. The distribution and brief interpretation of an urban thermal environment classes in the BMA region are shown in Figure 7a. The classes generated were named subjectively according to their dominant centroid attributes (where; Class 1—Extremely Low Density (ELD); Class 2—Very Low Density (VLD); Class 3—Low Density (LD); Class 4—Medium Density (MD); Class 5—High Density (HD);

Table 4. The ANOVA table indicates which variables contribute the most to cluster solution.

Variable	Cluster		Error		*F*	*Sig. p*-value
	Mean Square	*df*	Mean Square	*df*		
BCR	158.437	6	0.009	6,613	17,257.296	<0.001
FAR	25.879	6	0.003	6,613	9,339.448	<0.001
GCR	9.977	6	0.013	6,613	753.151	<0.001

Class 6—Very High Density (VHD); and Class 7—Extremely High Density (EHD)). The results from the CA can be presented on Figure 7b in which every cluster contains landforms that share similarities in their morphological attributes. The interpretation of each class was confirmed by visual inspection of 3-D view maps and building elevation profiles on Figure 8 and Figure 9, respectively.

According to the scheme of seven classes (Table 5), obviously, the 13 TCZs in the class 7 (here called the EHD areas) (~0.2% of total study area), as in the urban center or compact high-rise were located mostly in the central business districts of BMA such as Silom, Ratchadamri and Nana (Sukhumvit 13 Rd.); the 63 TCZs (~0.95%) as urban

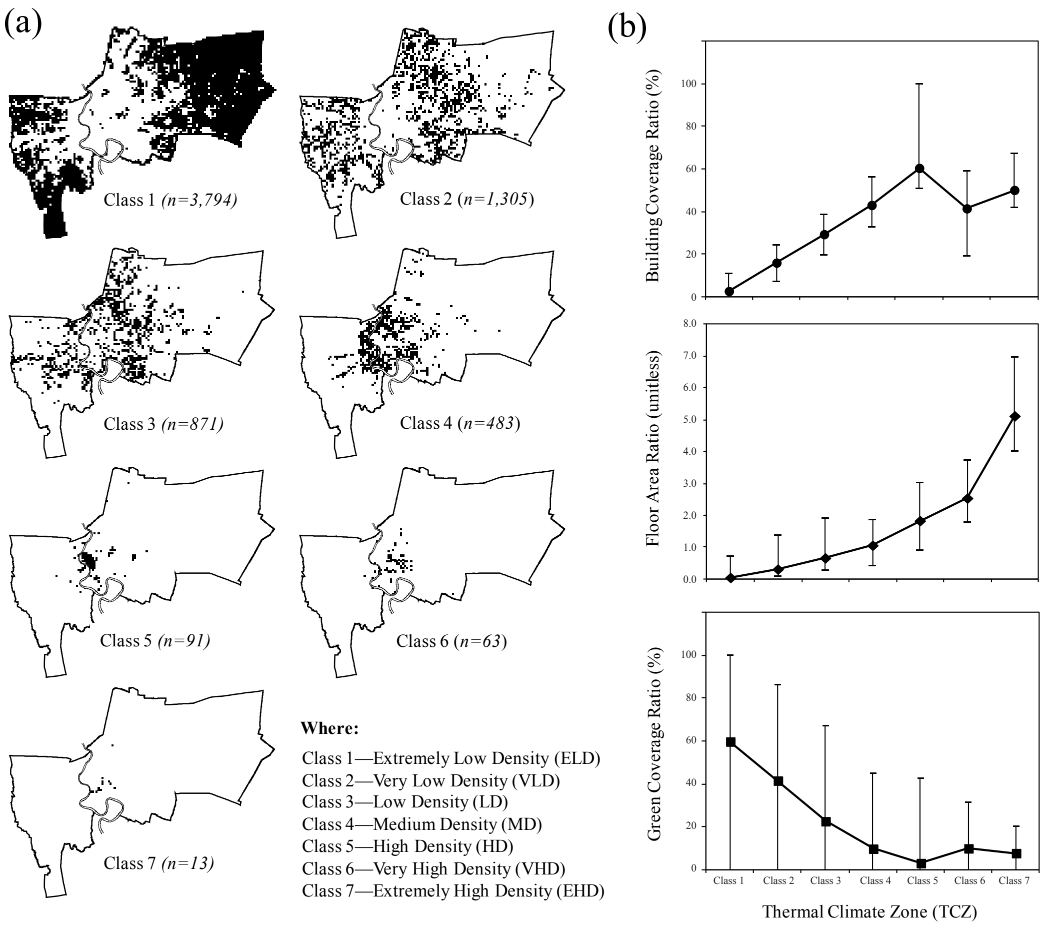


Figure 7. (a) Distribution of thermal climate zone classes, and (b) Mean values of the surface morphological variables of thermal climate zones.

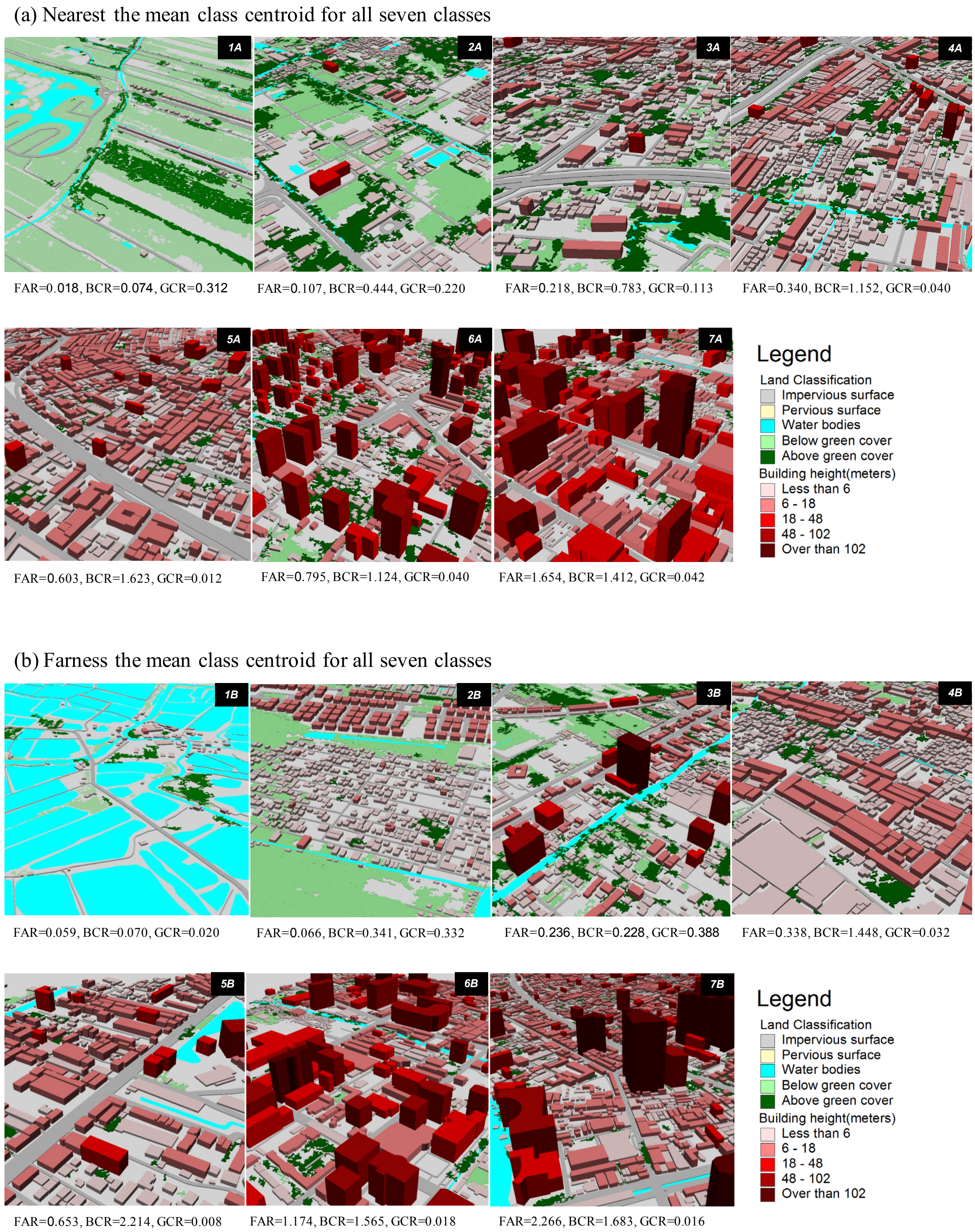


Figure 8. The 3-D views of Thermal Climate Zones (TCZs) typical for (a) Nearest and (d) Farness the mean class centriod of seven urban to rural landform classes.

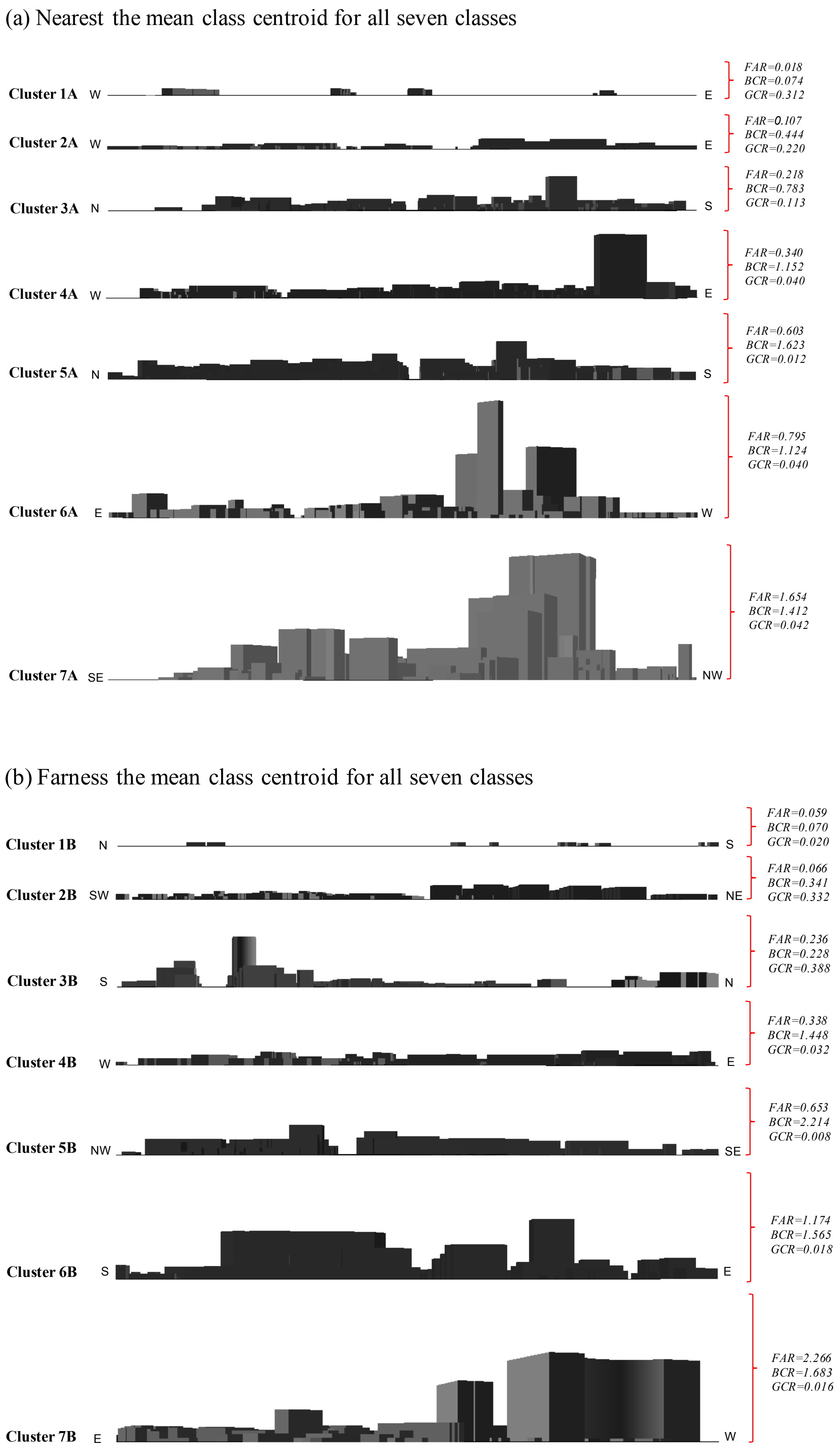


Figure 9. The building elevation profiles of Thermal Climate Zones (TCZs) typical for (a) Nearest and (b) Farness the mean class centriod of seven urban and rural classes.

area in the VHD were expanded mainly along the major roads (Sukhumvit Rd., Sathon Rd., Silom Rd., and Ari Rd.) and some scattered along the Chao Phraya River (the riverfront development; high-rise hotels and residence apartments); the 91 TCZs (~1.37%) in Class 5, obviously as the BMA's old CBD areas, were located mostly in the historic core districts (Yaowarat, Pra Nakhon, Pom Prap Sattru Phai, and Samphanthawong); the 483 TCZs in Class 4 (~7.30%), obviously as the compact midrise urban areas, were located mostly in the out edge of the Class 5-7 (the compact high-rise of urban core area); it was reasonable that the urban fringe as edge of the urban core was obviously enlarged in the metro-city; the 871 TCZs in Class 3 (~13.16%), as in suburb areas, dense mix of low-rise buildings (1-3 stories) and large low-rise industrial structures (industrial building or warehouse); the 1,305 LCZs in Class 2 (~19.71%), as in rural areas with open arrangement of low-rise and mix of single-story buildings; and the 3,794 TCZs in the Class 1 (~57.31%), as rural fringe areas, were located in the most area of BMA, beyond the suburban rural area. Finally, all zones of distinct urban morphologies arranged in approximate decreasing order of their ability to impact urban climate of Bangkok are summarized in Table 6. Each zone is individually named and ordered by distinguishing surface morphology property, which in most zones is the intensity of urban structures or the amount of green cover.

3.2 Major Factors Responsible for TCZ's Temperature Stability

The Land Surface Temperature (LST) has been shown to be highly correlated with the near-surface air temperature (Srivanit & Hokao, 2011, pp. 34-46; Srivanit & Hokao, 2012, pp. 83-100; Nichol & Wong,

Table 5. A simplified classification set of distinct urban morphologies arranged in approximate decreasing order of their ability to impact urban climate of Bangkok.

Zone name	BMA's TCZs[a] for each class			Zone morphology properties (Mean±SD)		
	Num. zones	Area Sq.km	%	*FAR* [b] (Unitless)	*BCR* [c] (%)	*GCR* [d] (%)
1. Extremely low density (ELD)	3,794	948.50	57.31	0.05±0.06	2.69±2.88	59.78±26.19
2. Very low density (VLD)	1,305	326.25	19.71	0.31±0.12	16.02±4.07	41.56±16.62
3. Low density (LD)	871	217.75	13.16	0.66±0.23	29.39±3.91	22.61±11.54
4. Medium density (MD)	483	120.75	7.3	1.06±0.28	43.09±4.60	9.81±6.86
5. High density (HD)	91	22.75	1.37	1.83±0.52	60.49±9.37	3.11±5.28
6. Very high density (VHD)	63	15.75	0.95	2.54±0.61	41.50±6.88	9.96±7.32
7. Extremely high density (EHD)	13	3.25	0.2	5.12±1.02	50.15±8.62	7.75±5.45

[a] The total of 6,620 uniform grid cells (cell size 300x300 m.)

[b] Ratio of the total covered area on all floor of all buildings plan area to total plan area (Unitless)

[c] Ratio of the impervious plan area (buildings footprint and artificial structures) to total plan area (%)

[d] Ratio of the green space covered (trees, grass, and cultivated plants) to total plan area (%)

Table 6. Abridged definitions for thermal climate zones (TCZs) of Bangkok.

Zone illustration	Zone definition	Zone illustration	Zone definition
	**Class 1: Extremely Low Density (ELD)** ❸ Rural development with scattered houses (e.g., cottage housing, or with one single-family structure) in natural scrubland or agricultural area. Featureless landscape of grass or herbaceous plants/crops and scattered trees. Open water bodies such as lakes and swamps, canals and reservoirs.		**Class 2: Very Low Density (VLD)** ❷ Semi-rural development with scattered houses, horizontal skyline of low-rise buildings (one- or two-story) and well separated by open, paved spaces. Including warehouses, wholesale, research and development, and manufacturing uses. Open arrangement of bushes, shrubs, and short, trees.
	**Class 3: Low Density (LD)** ❷ Low density suburban with smaller detached homes. Abundance of pervious land covers (low plants, scattered trees). Buildings separated by yards, and set along medium-width streets. Small commercial, multi-story mixed use and residential buildings.		**Class 4: Medium Density (MD)** ❶ Medium development with low-rise apartment buildings or townhouses, gardens, and small trees. Mixed houses and small shop. Warehouse, light industrial area or shopping mall with large low buildings & paved parking or open space.
	**Class 5: High Density (HD)** ❶ Highly developed urban with very close-set buildings (e.g., old town centers, dense row or detached and semidetached housing), Office/Mid-rise apartment building three- to nine-story large or closely spaced, semidetached and row houses. Few or no trees. Land cover mostly paved or hard-packed.		**Class 6: Very High Density (VHD)** ❶ Open arrangement of high-rise apartment buildings, residential-closely spaced less than four-story row and block buildings or major facilities, town center, narrow street canyons, e.g., modern city core, tall apartment, major institution. Abundance of pervious land cover.
	**Class 7: Extremely High Density (EHD)** ❶ Intensely developed urban with close-set high-rise buildings. Buildings are often large and dense, tall buildings, attached or close-set, and homogeneous in character with narrow streets. Heavy traffic flow. Few or less trees. Land cover mostly paved (e.g. concrete and grass construction materials)	**Remark:** Ephemeral or variable vegetation greenness index that change significantly with agricultural practices, and/or seasonal cycles. Permeability affects the moisture status of the ground and hence humidification and evaporative cooling potential. Level of action plan: ❶ : Strongly recommend to mitigate the existing condition; ❷ : Recommend to mitigate the existing condition; ❸ : Maintain or protect the existing condition.		

Table 7. Correlation coefficients between the variation of land surface temperature and surface morphological descriptors of thermal climate zones.

Variable	Thermal climate zone level							Urban level
	ELD	VLD	LD	MD	HD	VHD	EHD	
BCR	.608**	.532**	.484**	.455**	.871**	.470**	.346	.885**
FAR	.606**	.424**	.187**	.106**	.307**	.176	.313	.876**
GCR	-.134**	-.306**	-.225**	-.207**	-.278**	-.369**	-.468	-.577**

Note: Significant level at $^{**}p < 0.01$, $^{*}p < 0.05$

2008, pp. 7213-7223). The remotely sensed LST thus has often been used to assess the urban thermal environment due to its easy acquisition at a given moment and across broad areas. Such studies attempt to reveal the effects and reasons of UHI by linking spatiotemporal variations in LST with the surface morphology variables. The Spearman's rank correlation (Spearman's rho) was then used to examine the relationship between the mean LST variation and a group of selected structural features of TCZs in each cluster (reported in Table 7).

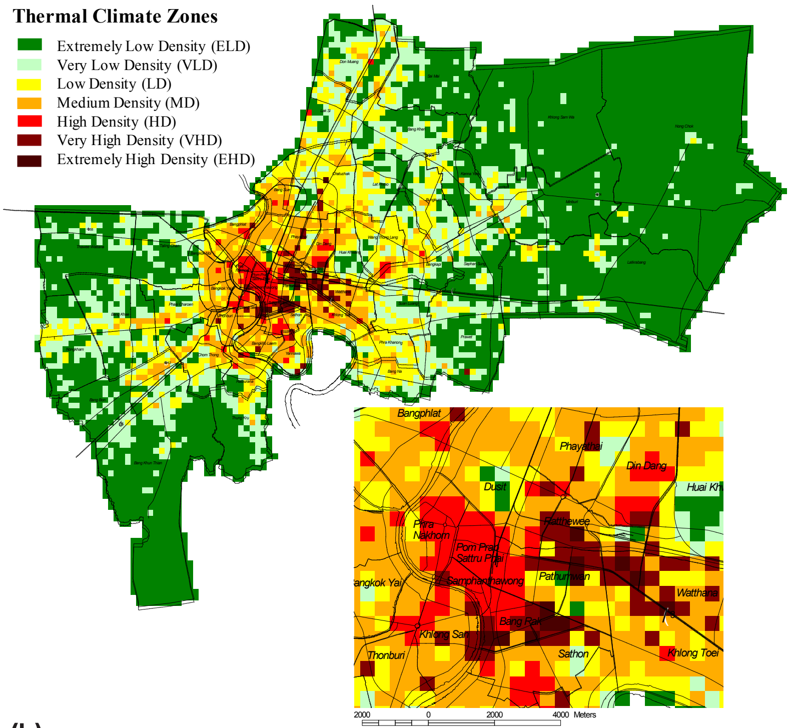
At the urban level, during summer daytime, the LST values increased from the outskirts towards the inner urban areas, which range from 35.38 to 43.84 °C, with a mean of 40.15°C. The fraction of BCR and FAR were found to be most positive correlated variables in explaining the regional LST variation (with a mean LST of ~41.72°C), which affects urban climate through its modification of heating potential of the surface structure and cover of the ground. In contrast, the GCR was negatively correlated, indicating that LST would decreases with cooling potential of the green spaces. At the TCZ level, the similarity in the highest LST variations of HD areas can be explained by similar surface morphological characteristics relating to a high proportion of built-up surface covers (usually have more impervious area and flat roofs concrete) and a lowest amount of green space. These areas were mostly located in the downtown core area such as Yaowarat District; is now known as the old CBD area, the building was converted into a biggest retail and wholesale trading center, and the area is bordered by the Chao Phraya River to the south.

The lowest LST variations were observed for low density residential, agricultural and/or natural cultivation zones (with a mean LST of ~37.49°C). These variations may be primarily to vegetation such as grass, paddy filed or trees often found around the built structures in these TCZs, and serve as *"cool islands"* in urban region during summer. Specifically, the EHD areas are not significant correlations with the regional LST variation, which occupied the largest proportion of vertical intensity with buildings in urban areas, and had the high impacts green spaces than the HD areas. This implied that the regional LST variation may limits to analyze contribution of these areas, where the tall buildings were delimited from the shadows to identify on a LST of LANDSAT TM image. The TCZ types in order from highest to lowest LST variations were shown in Figure 10.

4. Discussions and Conclusions

In recent years, there has been an increasing awareness and trend to integrate climatological elements in urban environmental planning and management. The awareness of urban planners, architects and decision makers of environmental problems and of the need to improve the quality of living necessitates the integration of climatological factors in city planning. On the other hand, urban planners were interested in climatic aspects but the

(a)



(b)

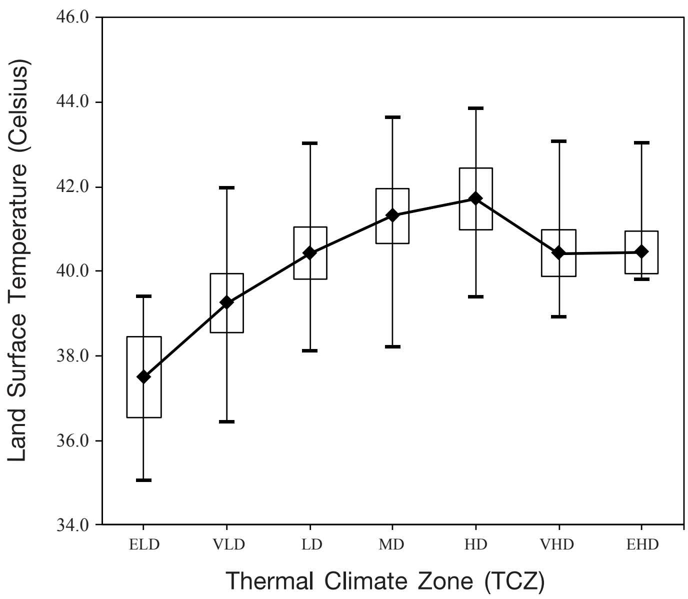


Figure 10. (a) An urban thermal environmental map (UTEMap) and (b) the stability of surface temperatures for different thermal climate zones in the summer of BMA.

use of climatic information was unsystematic, especially climatology has a low impact on the planning process. In Thailand, the urban climatic environment has never been studied systematically at the urban level and applied to the Thailand Planning System. This research is at the beginning stages of urban climatic information and knowledge, which has been applied to the city planning of Bangkok. This study was performed using GIS as the data platform to ensure that the effectiveness of spatial tool, which has been the working tool of urban planners. Then, integration of surface morphological data was done by calculating the area of the morphological attribute with respect to the urban and rural landform to which it belongs. The main advantage of this method is the hierarchical system that is to be able to describe the city-wide and local levels, and a set of indicators that reveals what defines the urban temperature levels. The determination of statistically significant variables that is characteristic to each climate zone and the interconnection between the TCZ classification and the GIS software that helps to visualise and further analysis.

The final result is an UTEMap with an attached table or legend in which the main characteristics of the surface morphological properties are displayed. Moreover, very high thermal load problem areas and urban climatic sensitive areas in Bangkok were identified, as well as needing more attention and mitigation measures in different thermal climate zones. With the approach proposed here, TCZs are delineated taking into account their variables which comprise a set of landforms which have similarities in their thermal environment attributes. Using landforms as spatial units of reference to delineate local climate and environmental units seems to be optimum for urban environmental planning and management since it allows a fast integration of several morphological and environmental attributes into a single landform that can be grouped with other landforms to conform local climate units. The production of an UTEMap can be obtained in a relative short time if the GIS-multivariate analysis approach is used for urban and rural landform delineation.

This classification can now be used as a structure for surveys and planning, to answer questions such as "What is the total green cover in the Bangkok metropolitan region and what are the uncertainties associated with the estimates?" "How much open space is available for future urban tree planting in the BMA?" "What is the effect of present and possible future tree volumes on urban temperature in the BMA?" This information could be of interest to city planners and urban designers, recreation and amenity officers, and landscape ecologists, to conduct more detailed survey of each zone according to the application of interest (e.g. green infrastructure planning (Vanno, 2012, pp. 1-13), future tree planting tree planting potential, greening premises, greening rooftops, increased rooftop reflectance, derelict sites, sites suitable for recreational development, new woodland planting, etc.), which can be extrapolated to the whole Bangkok region. Moreover, given that the thermal climate zones classification methodology can be applied to other metropolitan areas where surface morphological data is available, the same kind of questions may be addressed in these areas.

These are examples of the wide range of potential applications for a thermal climate zones classification system, of interest and use to local authority planners, property developers, environmental researchers, and policy makers. The classification system described here is useful for stratified planning and extrapolation where resources are scarce. It is simple to apply to other rapid growth cities in Thailand, and indeed to any region for which there exists a spatial dataset consisting of attribute data to describe the component morphological properties of each zones. Thus, this methodology provides an alternative for urban environmental studies, and may be applied to other cities in the tropical climate. Moreover, the findings of this study can be employed to develop a theoretical basis for better urban planning policies to mitigate the UHI effects. At the same time, effective mitigation measures are not clear or actionable for planners. Thus, further work is an urgent needed to establish a possible urban climate change adaptation and mitigation strategies for Bangkok by focusing on the improvement or preservation of existing greenery, creation and protection of ventilation paths and reduction of thermal load in built-up areas by controlling parameters of urban morphology.

The largest fuzzy class membership grade of the seven thermal climate zone classes for any individual zone should correspond to the climate class allocated to that zone. In fact, in joining a new TCZ to a growing class, it is possible that the TCZ that minimizes overall variance at that point in the agglomerative clustering process is not necessary that the TCZ whose attribute values are nearest to the mean class centroid. This is a virtual certain in any active urban area as land clearance and development occur. Updating TCZ designations is needed and crucial for all zones, particularly those used in long-term thermal environment studies. The changing site will "progress" or "regress" through the natural, built environment, compact, and open forms of the TCZ classification. Thus, it has been no longer ignore for a requirement of a guideline for updating the TCZ classification system for collecting appropriate site metadata to quantify and update the surface properties of zone annually.

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