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Applying "Local Climate Zone (LCZ)" into a High-density High-rise Cities - A Pilot Study in Hong Kong

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1. Introduction

During the past few decades, the urban development's impact on urban climatic condition has been reported throughout the world. It is well recognized that site morphology and geometry can modify the local climatic condition and form its unique climatic characteristics. Thus, describing physical site properties in a scientific and precise way is important and necessary for urban climatic analysis and application into urban planning. Tim Oke initiated a scheme of urban climate zone (UCZ) in 2004 (Oke, 2004 & 2006) and later in 2009 Iain Stewart and him further developed a refined comprehensive approach of "local climate zone (LCZ)" classification by using a standardized and quantitative way to present physical surface properties of sites and their local climate features(Stewart & Oke,2009 & 2014).

LCZ classification has 17 standard types including two subsets: 10 built types and 7 land cover types. Each LCZ can be defined quantitatively by using a standard set of parameters. Some case studies have been conducted in cities of Sweden, Japan and Canada, which are located low density city. Unfortunately, there has been no study testing LCZ classification in high-dense cities. The study wishes to fill this knowledge gap by focusing on high density built-up types and land cover types of Hong Kong. Using field measurement, computational numerical simulations, information regarding the metadata and meteorological data could be collated.

This paper firstly examines long term archives of meteorological observations from Hong Kong Observatory (HKO) automatic weather stations (AWSs) to identify the typical weather condition in summer, find out the linkages of UHI intensity with cloud amount and wind speed, and analyze the diurnal cycle of UHI intensity. UHI intensity is found to be maximized during calm and clear nights based on annual statistics. However, peak UHI intensity in summer has been recorded under partially cloudy and calm wind condition since the clear sky day only accounts for 2% of the summer period. Secondly, this paper analyzes air temperature data captured by five mobile traverse measurements at street level (2.3m above ground) during partially cloudy and calm summer nights (8PM to 10PM) in 2014 to study the UHI intensity pattern over three high-density urban areas: northern part of Hong Kong Island. Selected samples sites for traverse measurement have been determined following the Local Climate Zone (LCZ) scheme, covering the six LCZ classes of Compact High-rise (CH), Open High-rise (OH), Compact Mid-rise (CM), Open Mid-rise (OM), Compact Low-rise (CL) and Open Low-rise (OL). Thirdly, morphological and geographical parameters of building height, building coverage ratio, building volume density, sky view factor, street coverage ratio, park coverage ratio and altitude automatically calculated by GIS have been compared with traverse measurement data. Stepwise multiple linear regression has been applied to find the best fitting model for UHI intensity estimation. Finally, a LCZ map and an UHI intensity estimation map have been developed to describe the distribution of LCZ classes over Hong Kong and predict the associated UHI situation for planning reference. The information would allow the formulation of urban planning guidelines and climatic spatial design strategies based on a set of threshold value of urban morphology and its climatic impact.

2. Objective

This study aims to (1) apply LCZ scheme to subtropical high-density city of Hong Kong and develop a LCZ map of Hong Kong based on land cover classification of built-up regions; (2) use Geographical Information System (GIS) to establish an information platform integrating morphological datasets and climatic datasets, and also report the statistics in a standardized manner recommended by LCZ scheme (Stewart, Oke, & Krayenhoff, 2014) to foster data exchange across regions and interdisciplinary communication between researchers and planners; (3)

investigate the spatial pattern of urban heat island and intra-urban air temperature variation across high-density areas of Hong Kong using traverse measurement under typical summer weather, and analyze the relationships between urban form and local thermal conditions; (4) discuss the adaptation and mitigation strategies for thermal environment improvement in high-density scenario of Hong Kong.

3. Method

3.1 Pilot Study Areas

Hong Kong lies on southeast coast of China (22° 16’ 50” N, 114° 10’ 20” E), with total area of about 1104 square kilometers covering Hong Kong Island, Kowloon and the New Territories and Islands. The terrain of Hong Kong is hilly and mountainous with steep slopes, where the elevation ranges from sea level to over 900m above sea level (Dai & Lee, 2002). Hong Kong has monsoon-influenced subtropical climate along with seasonal variation in temperature, wind direction, humidity and precipitation. The summer prevailing wind direction is southwest while the wind in winter mainly comes from east(HKPD & CUHK, 2009). Though the average wind speed measured on the islands around Hong Kong Island and Kowloon Peninsula is high (6.92 m/s at 26.3 m above ground level)(Lu, Yang, & Burnett, 2002), the actual wind speed inside compact urban areas is weak due to the block of dense buildings.

Hong Kong is one of the most densely populated and constructed cities over the world with impressive skyline depicted by skyscrapers along the coast. However, it is not precise to simply summarize urban morphology in Hong Kong as “high-rise and high-density”. Owning to the mixed land use planning, land surface geometry in Hong Kong exhibits great variability from compact high-rise central business area, compact mid-rise old town and open low-rise aboriginal settlements to woodlands, farmlands and sandy beaches covering most of the LCZ classes. Therefore, the highly urbanized and compact districts of northern Hong Kong Island are selected as study areas.

3.2 Local Climate Zone (LCZ)

Local morphology forms its local meteorology. Local scale ranges from 10^2 to 10^4 meters distinguished by urban surface properties, and varies across regions and cities (Stewart & Oke, 2009). Houet and Pigeon (2011) compared the UCZ classification of Toulouse (France) in 100m, 250m and 500m radius and concluded that landscape variables computed at 250m radius best fitted Oke’s UCZ classification. Source area size for LCZ classification in Nagano (Japan), and Uppsala (Sweden) is around 100m radius in city center and 200m radius in outskirt, while appropriate size for Vancouver (Canada) is around 200m radius (Stewart et al., 2014). Leconte et al. (2015) reported that many LCZ sites in Nancy (France) slightly exceed 400m diameter. Middel et al. (2014) adopted 115m/120m-length size into the simulation of mini neighborhoods under different LCZ classes. Compared to the above cities where LCZ sites are mainly consisted of mid-rise or low-rise residential neighborhoods, general dimension of buildings and street blocks in Hong Kong is larger. On the other side, urban morphology at district level shows greater diversity than other cities influenced by the mixed land-use type, coastline and hills. Based on the field observations and GIS analysis, LCZ size in 100m*100m, 400m*400m or 500m*500m may be too small/large for LCZ classification in Hong Kong. Chen et al. (2012) concluded that SVF calculated at 150m radius can best explain the intra-urban air temperature difference compared to the values calculated at 50m, 100m and 200m radius in high-rise and high-density areas of Hong Kong. Ng et al. (2011) also reported that urban morphology at podium layer in 300m*300m resolution performed better than that in 200m*200m resolution in predicting local wind environment in Hong Kong. Therefore, size of study sites for LCZ classification in Hong Kong is determined as 300m*300m.

According to the LCZ classification framework, type of landscape (building or plant), height of objects, and density of objects are the three aspects for logical division. Thus, building height map and ground coverage map in Hong Kong were computed automatically using GIS data to identify the sample sites inside the study areas. Six LCZ classes, including compact high-rise (CH, LCZ1), open high-rise (OH,LCZ4), compact mid-rise (CM, LCZ2), open mid-rise (OM, LCZ5), compact low-rise (CL, LCZ3) and open low-rise zones (OL, LCZ6), have been identified in high-density urban areas in Hong Kong (Figure1). Figure 2 shows the spatial distribution of LCZ sample sites and traverse measurement route in northern Hong Kong Island. Northern Hong Kong Island (HKI) is a highly urbanized area, which is developed along the narrow plain between the coast and the hills. It is mainly consisted of commercial, residential, government and institute land use, and covered by densely built high-rise buildings. There are two LCZ classes of CH and OH identified along the traverse measurement route in HKI.

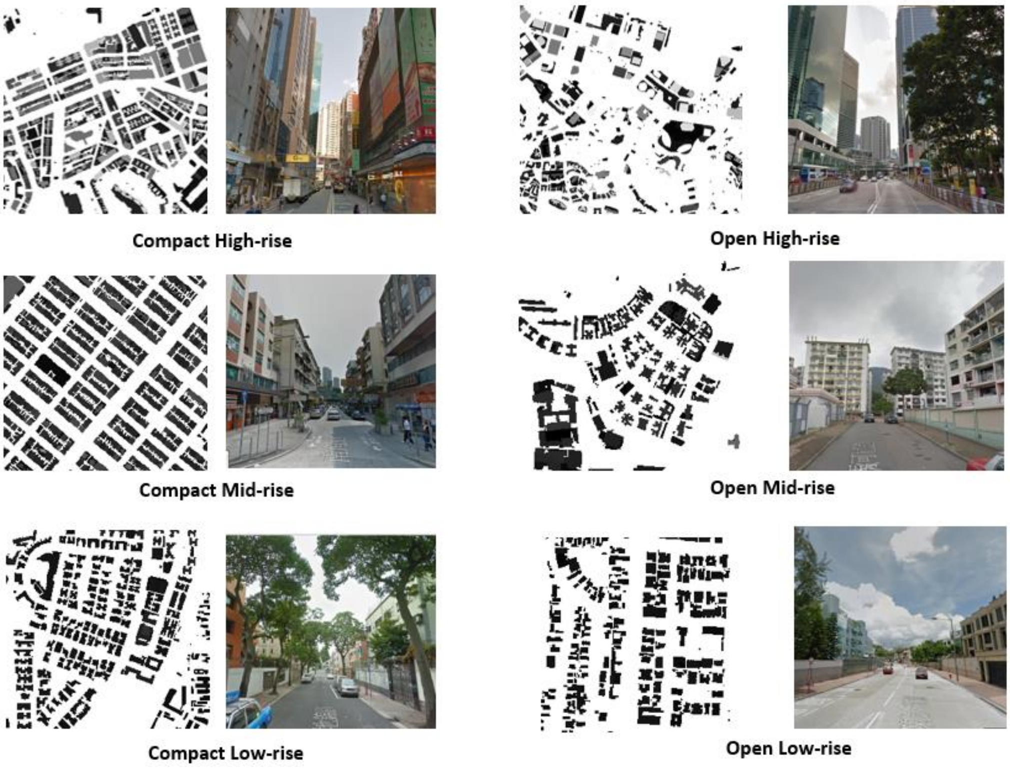

Figure1 Examples of LCZ classes in Hong Kong

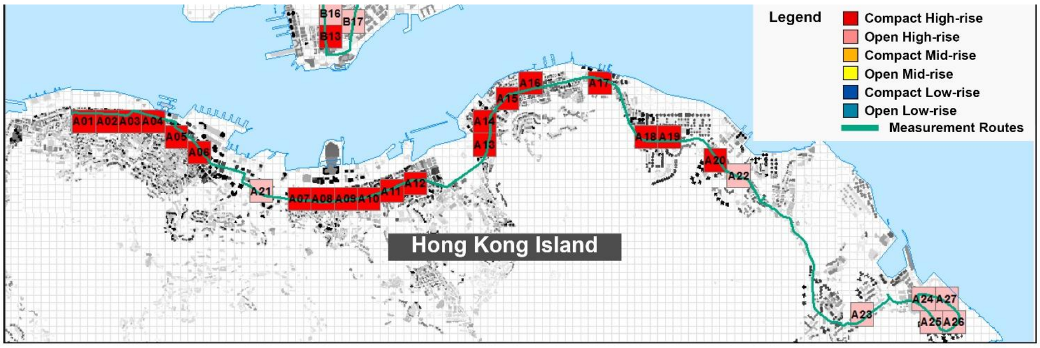

Figure 2 Location of sample sites and traverse measurement routes

3.3 Data

Three datasets are used to classify the urban surface and quantify the relationships between urban morphology and climatic conditions at local scale. Dataset I consists of morphological data from Planning Department of Hong Kong. Dataset II comprises stationary observation data from automatic weather stations of Hong Kong Observatory (HKO). Dataset III includes local meteorological data in high spatial resolution captured by nighttime traverse measurements across the study areas.

4. Results and Analysis

4.1 Intra-urban Climatic Variation

According to the above analysis of prevailing summer weather condition and the associated UHI behavior in Hong Kong, traverse measurement time has therefore been determined as 20:00 - 22:00 under partially cloudy and low wind weather condition. Five times of traverse measurements (2 measurements in Hong Kong Island) were conducted to scan the spatial distribution of meteorological parameters inside high-density urban areas. Table 1 shows the meteorological information recorded by reference stations of HKO, TKL and WGL, weather condition during five measurements were basically consistent in wind speed and cloud cover. Wind speeds observed at HKO were under 2m/s, while sky conditions were partially cloudy with cloud amount (observed at HKO) of 30-40% except July 16 at 78%. There was no rainfall recorded in the past 24 hours before each measurement at nearby stations of study area as well as rural reference station of TKL to ensure that the thermal differences were not changed by precipitation.

Table 1 Dates of traverse measurement and associated background weather conditions recorded by HKO, TKL, and WGL stations. (Air temperature (Air Temp.), wind direction (Wind D.) and wind speed (Wind S.) are average value during the measurement time from 20:00 to 22:00, while cloud amount is daily mean value reported by HKO.)

Date	Route	Time	HKO		TKL			WGL	
			Air Temp.	Cloud Amount	Air Temp.	Wind D.	Wind S.	Wind D.	Wind S.
Jul 16	HKI	20:00 – 22:00	30.0 °C	78%	28.7 °C	E	1.43 m/s	E	4.44m/s
Aug 26	HKI	20:00 – 22:00	29.5 °C	40%	28.1 °C	E	1.87 m/s	E	4.97m/s

Figure 3 and 4 show the spatial distribution of air temperature and relative humidity along the measurement routes in HKI (Jul. 16 & Aug 26). Air temperature and relative humidity was basically in inverse relationships. On the whole, higher air temperature was observed in compact urban areas than open urban areas as expected. Downtown commercial areas of Causeway Bay in HKI are suffered most severe nocturnal thermal environment. Compact High-rise (CH) and Open High-rise (OH) are the dominant LCZ classes in HKI. Thermal variability also existed within same LCZ classes that highest UHI intensity difference over 1°C occurred within CH class and also within OH class in HKI. Cooling effect from large urban parks and coast is significant that CH site A13 near Victoria Park (HKI) were significantly cooler than the nearby sites. Contribution of surrounding high-density morphology to temperature elevation of urban space was observed in e.g. CH site of A12 located in the central urban areas. Meanwhile, contribution to air temperature increase from traffic heat release is also notable. Air temperature collected in site samples near urban freeway or main road was higher than expected.

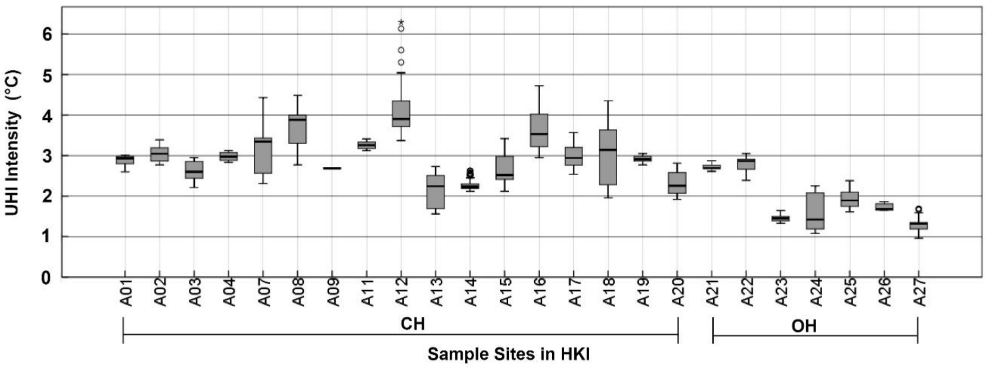

Figure 3 Boxplot of air temperature measured in Hong Kong Island (Aug 26),

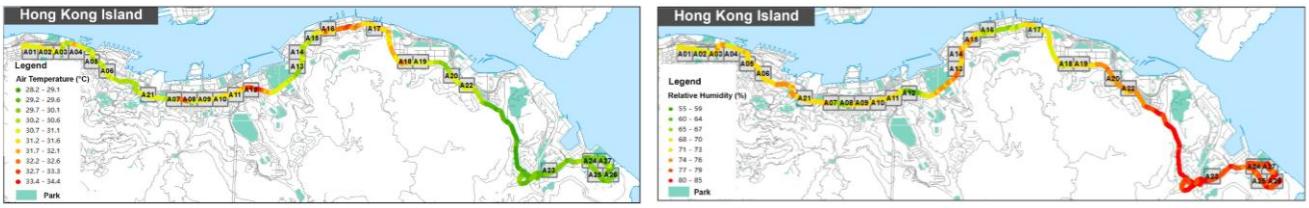

Figure 4 Measured Air Temperature and Relative Humidity in Hong Kong Island (Jul.16 & Aug. 26)

4.2 Impact of morphological parameters on local climate

In this study, the relationships between nocturnal UHI Intensity (TKL station as rural reference for calculation) at neighborhood level and urban morphological parameters have been examined. Morphological parameters of Sky View Factor (SVF), Building Volume Density (BVD), Building Height (BLDGH), Building Coverage Ratio (BCR), Street Coverage Ratio (SCR), Park Coverage Ratio (PCR), and Altitude (MASL) have been taken into consideration. SVF, BVD, BLDGH, BCR are all urban density indicators: SVF and BVD are comprehensive indicators widely used in urban climate studies, while BLDGH and BCR are design parameters well known by planners. It can be found that SVF has the strongest linear relationship with UHI Intensity among the 7 morphological parameters. There are also existing strong linear relationships among the urban morphological parameters of SVF, BVD, BLDGH, and BCR. Thus, SVF, BVD and BLDGH & BCR are divided into three morphological groups together with traffic (SCR), greenery (PCR) and topographical (MASL) parameters into the multiple-linear regression with UHI Intensity. Scatterplot matrix in Figure 5 shows that UHI Intensity tends to increase as the urban density increases with raise in BVD, BLDGH, BCR, SCR and decrease in SVF. On the other hand, UHI intensity shows a slight downward trend when PCR and MASL rises.

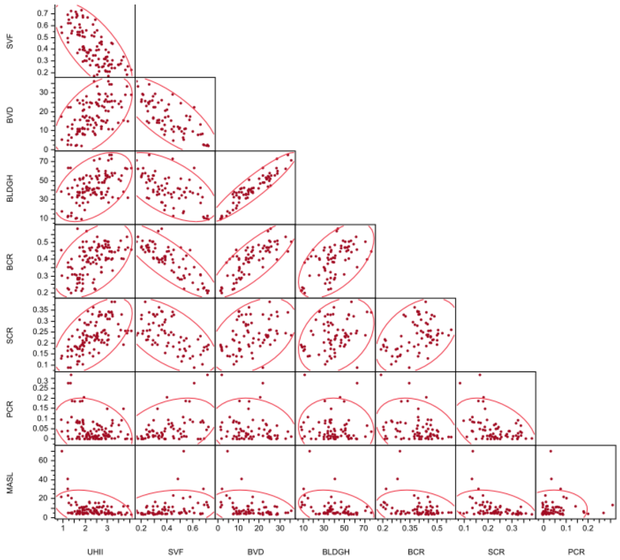

Figure 5 Scatterplot of UHI Intensity and urban morphological and topographical parameters

Stepwise multiple regression analysis has been applied to examine all possible subsets of above parameters and find the best fitting model. It can be found that, SVF can predict 50% of nocturnal UHI intensity variation compared to BVD (R^2 = 0.19), BLDGH & BCR (R^2 = 0.30). A combination of SVF, and SCR performs best in the model selection criteria (AICc, BIC , Cp and RMSE), and explains 55% of UHI Intensity. SCR contributes to temperature elevation since it can be affected by the traffic volume and the associated traffic heat release. However, as the park coverage of sample sites in high-density urban areas is low (generally under 10%) and the variation in elevation is not significant, PCR and MASL does not exhibit significant influence on the regression analysis. Therefore, nocturnal UHI Intensity in central area of northern Hong Kong Island can be modeled as:

$$UHII = 3.11 - 3.11 * SVF + 2.73 * SCR \quad (R^2 = 0.55) \qquad (1)$$

4.3 Development of LCZ map in Hong Kong

LCZ scheme was originally developed to classify urban areas for UHI observation and standardize the morphological and climatic report for better application into planning process. Mapping method was not initially integrated in the LCZ scheme, as the grid network of raster-based map may not fully follow the LCZ boundary and therefore create some mixed type grids (e.g. mixture of CH&OH, CH&CM) rather than typical LCZ grids. However, development of LCZ map over Hong Kong is important for planners to identify the spatial characteristics of urban morphology at city level, recognize the geographical potential of neighborhood sites at local level, and calculate morphological statistics. Thus, LCZ map in Hong Kong has been developed as a climatic planning support following the logical division of LCZ scheme: zonal average of building coverage ratio and building height was automatically calculated using GIS to classify the surface properties in density (compact/open) and height (high-rise/mid-rise/low-rise). Distribution of 6 urban zones of Compact High-rise, Open High-rise, Compact Mid-rise, Open Mid-rise, Compact Low-rise, Open Low-rise have been classified, and the non-urban regions covered by vegetation and water have also been visualized (Figure 6). As Figure 6 shows, urban areas in northern part of Hong Kong Island and Kowloon Peninsula are mainly covered by compact/open high-rise and mid-rise LCZ classes. Low-rise morphology occupies large areas of the New Territories, especially the northwestern part of Hong Kong.

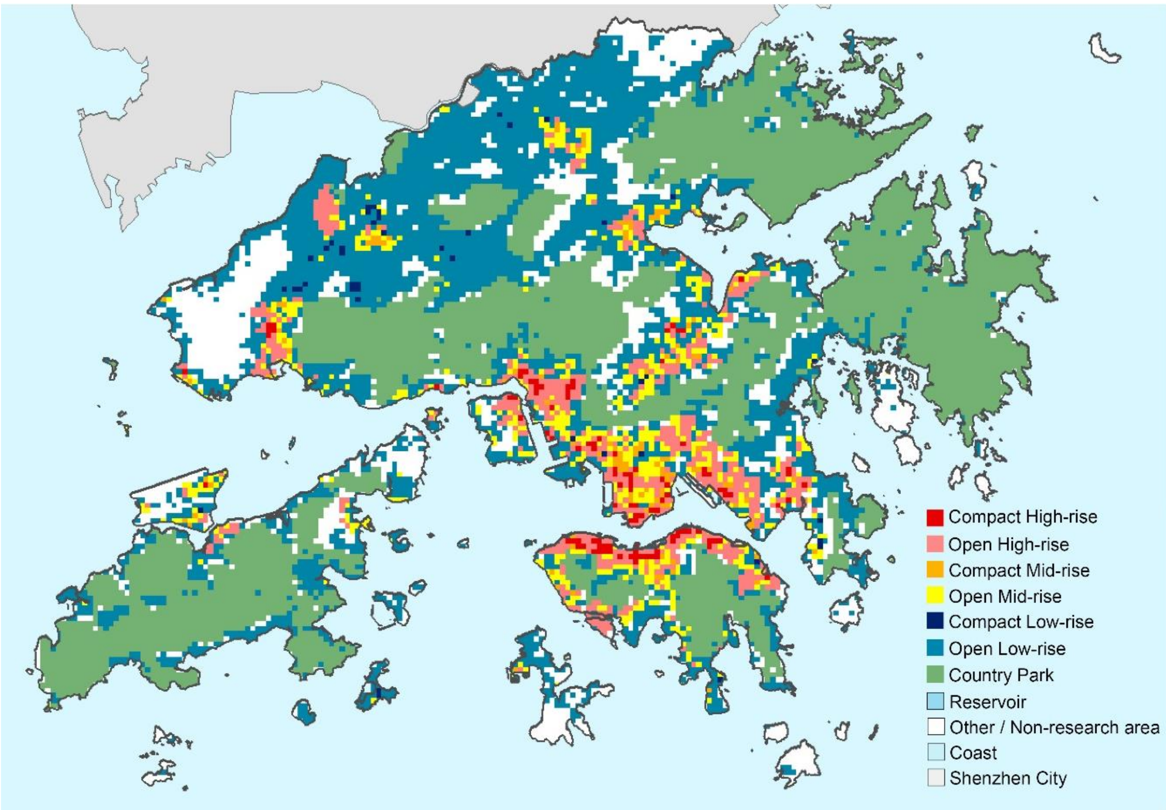

Figure 6 LCZ map in Hong Kong

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