Mapping the Local Climate Zones of Urban Areas by GIS-based and WUDAPT Methods: A Case Study of Hong Kong

Highlights:

- Both GIS-based and WUDAPT methods are suitable for detecting different LCZ classes of high-density urban areas.
- GIS-based method has higher accuracy in LCZ mapping, especially at district level.
- GIS-based method is suitable for capturing urban details.
- WUDAPT (level 0) method is appropriate for mapping LCZ at city level.
- WUDAPT (level 0) data can be used as input data for weather and climate models, like Weather Research and Forecasting model.

Abstract
Local Climate Zone (LCZ) developed by Stewart and Oke has become an international standard to analyse urban morphology and the corresponding urban heat island phenomenon. Primary methods for LCZ mapping include in-situ measurements, geographic information system (GIS)-based and remote-sensing-image-based calculations. However, there are few studies discussing their accuracy and suitability. This study focuses on examining and discussing the GIS-based method and the World Urban Database and Access Portal Tools (WUDAPT) Level 0 method. Hong Kong is selected as the study area due to its complex urban morphology and high-density context. The results show, at a city level, both methods can detect LCZ classifications that match with the actual spatial distribution of land use in Hong Kong. Thus WUDAPT level 0 data can be used as input data for mesoscale weather and climate modelling, when lacking precise urban morphology data. Meanwhile, at a district level, the GIS-based method detects more details than the WUDAPT method. However, WUDAPT method classifies land cover types more accurately. These findings provide an in-depth understanding of different LCZ mapping methods and their advantages and limitations. It can also help climatologists, modellers and planners select an appropriate LCZ mapping method for their studies of urban climatic applications.

Keywords: Local Climate Zone (LCZ), WUDAPT (World Urban Database and Access Portal Tools), High Density City, Urban Heat Island (UHI), Hong Kong

1. Introduction
Urbanization in the past half-century has not only changed the physical environment in cities, but also formed local climate characteristics and features unique to urban areas (Esser, 1989; He et al., 2007; Lam, 2006; Lambin et al., 1999; Oke, 1987; Zhou et al., 2004). The Urban heat island (UHI) effect is regarded as one of the most significant consequences of urbanization and industrialization in the 21st century (Wang and Bai, 2008). It is also a popular topic investigated internationally by various approaches and techniques. LCZs are the first attempt to standardize urban climatic studies across the world. Since then, many studies in this field have adopted this concept and method. The concept of LCZ also makes cross-comparisons between different UHI studies world-wide possible because of a standardized LCZ definition and classification hierarchy. More importantly, the output data and the understanding of LCZ classification can be potentially used for weather and climate modelling and other applications since urban information is much needed for climate change research (Pachauri et al., 2015) and climatic-responsive design (Bechtel, 2011; Cleugh et al., 2009; Grimmond et al., 2010; Ng and Ren, 2015).

1.1 Local Climate Zone studies
1.1.1 Local Climate Zone (LCZ)
The merit of the LCZ scheme lies in its detailed classification of urban land-use type. LCZ scheme serves as a standardized and quantitative method to describe the physical properties of urban morphology and explain their corresponding urban climatic properties (Stewart and Oke, 2009; 2010). There are 17 types of LCZ, including ten built types (LCZ 1-10), and seven land cover types (LCZ A-G) (Stewart and Oke, 2009; 2010). The properties of each LCZ class can be differentiated by metadata, including sky view factor (SVF), aspect ratio, building surface fraction, impervious surface fraction, pervious surface fraction, height of roughness elements, and terrain roughness class (Stewart and Oke, 2012). According to the LCZ scheme, different cities can classify and develop their own LCZs after analysing land use types, morphology features and functions (Stewart and Oke, 2009). LCZs generated following the same scheme help examine UHI phenomenon in different cities.

1.1.2 Primary methods of LCZ classification

The primary methods include in-situ measurement, GIS-based and remote sensing image-based analysing methods. These methods have their own advantages and limitations. In-situ measurement is the most basic method used in LCZ classification. It makes use of an electronic distance meter and the global positioning system to conduct field measurements (Thomas et al., 2014). The measurements record corresponding LCZ's parameters, which are the grounds for subsequent LCZ class identification. An obvious advantage of in-situ measurement is its ease of operation, but the high time and labour costs involved limit its popularity.

GIS-based methods are common techniques for mapping out LCZs. It relies on precise GIS data of urban morphology, planning and even building information to calculate each contributing factor for classifying LCZs. Several researchers use this method to develop LCZ classification maps of their target regions (Perera et al., 2012; Lelovics et al., 2014; Gál et al., 2015). Since the metadata of GIS-based methods are derived from real urban morphologies, GIS-based methods can usually achieve high accuracies. However, not every city's GIS data are complete or accessible to the public, especially in developing countries and regions.

The remote-sensing-image-based method is another widely used way to classify LCZ classes. Different kinds of remote sensing image classification methods are applied to extract LCZ classes by analysing their spatial and spectral information, including object-based image analysis, supervised classification, hierarchical classification with different Normalized Difference Vegetation Indices, and multi-source satellite images (Bechtel et al., 2016; Lin and Xu, 2016). Several kinds of remote sensing images (such as Landsat images, panchromatic VHR, short for "Very High Resolution" data, synthetic aperture radar images, etc.) are used as input data for LCZ classification (Bechtel et al., 2015; Bechtel and Daneke, 2012; Gamba et al., 2012; Lin and Xu, 2016; Mitraka et al., 2015). Among these satellite image-based LCZ classification methods, World Urban Database and Access Portal Tools (WUDAPT) is a global initiative and a community-based volunteer program. It aims to develop an easily achievable LCZ classification scheme that makes use of free data sources, such as Landsat images and training samples from Google Earth (Bechtel et al., 2015; Bechtel et al., 2016; Mills et al., 2015). Thus, many world-wide researchers have adopted and applied the WUDAPT method in their UHI studies (Brousse et al., 2016; Cai et al., 2016; Kaloustian and Bechtel, 2016; Verdonck et al., 2016). It aims to provide products of three levels: Level 0 contains mainly 2-dimensional urban morphological information and rough urban function based on their effect on the local air temperature (Mills et al., 2015; Stewart and Oke, 2012); both Level 1 and 2 provide more detailed 3-dimensional urban morphological information, material composition data and anthropogenic functions at building level, so they are suitable for various weather and climate models (Ching et al., 2017). There are four main advantages of the WUDAPT method:

(1) WUDAPT level 0 method follows a specific standard and procedure for data collection and data processing;
(2) required data, software and generated results of WUDAPT are free and can be publicly accessed;
(3) anyone can refer to, share and process these results further;
(4) the data generated from this process can be applied to other studies, such as weather and climate modelling, urban planning, and public health (Feddema et al., 2015).

1.2 Research gap and objectives

Although various classification methods have been developed since the LCZ scheme was proposed, there are limited cross-comparison studies carried out to examine the classification accuracy of different LCZ mapping methods, as well as their suitability for applications (Gál et al., 2015). Thus, this study focuses on both GIS-based and WUDAPT level 0 methods to analyse their advantages and limitations, and explore their suitability for potential applications at both city and district levels.

Hong Kong is selected as the case study city due to its complex urban morphology and the availability of data. Performance evaluation is also conducted to determine both methods' applicability. The results of the study can help researchers select an appropriate LCZ mapping method, and further develop and improve their accuracy.

2. Methodology

2.1 Site and location

Hong Kong is located at the south coast of China. It has a humid subtropical climate. According to the historical records of Hong Kong Observatory (HKO), urban wind speed has continued to decrease and urban air temperature has increased over half a century of urbanization since the 1960's (Lam, 2006). These conditions can aggravate the UHI effect in the downtown areas of Hong Kong.

Hong Kong is famous for its unique urban morphological characteristics and high-density land utilization (Fig. 1). The city covers 1104 km^2 of land and has a population of over 7 million (Census and Statistics Department of Hong Kong, 2011). Most area of Hong Kong is hilly and rugged and liveable land covers less than a fourth of the entire area of Hong Kong, distributed mainly along the Victoria Harbour, on the Kowloon Peninsula, and in the northern parts of New Territories (Census and Statistics Department of Hong Kong, 2006; Morton and Harper, 1995). Since the 1970s, the Hong Kong government has been developing new towns to cater for the booming population. Kowloon as an area developed at an earlier stage and Yuen Long as a new town were selected for an accuracy comparison at a district level (Fig. 1). Details about their background and urban context will be explained in section 3.3.

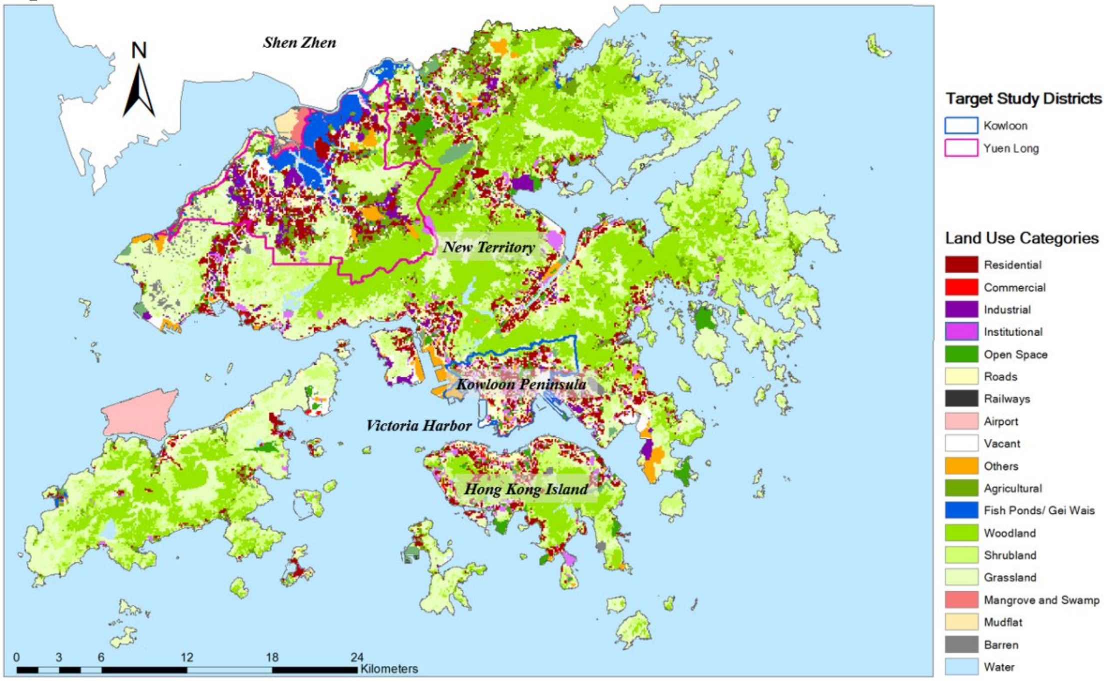

Fig. 1 Land Utilization Map of Hong Kong with Target Districts (based on Planning Department of Hong Kong, 2009)

2.2 WUDAPT level 0 method

2.2.1 Data

WUDAPT level 0 method employs free remote sensing images (Mills et al., 2015). In this study, Landsat 5 satellite images were selected as input image data because they contain urban structure information, like thermal information from band 6, which can be used to classify and map LCZs (U. S. Geological Survey, 2013). They can also provide 30-meter-resolution images covering the earth every 16 days (U. S. Geological Survey, 2013).The images can be freely downloaded from the U. S.

Geological Survey website. The essential selection criterion for the satellite images is to avoid cloud cover which affects the subsequent processing and the final product's overall quality. The below Landsat images of Hong Kong (Table. 1) were selected after considering the images' availability and quality.

Table. 1 Description of Input Data for WUDAPT Method (Landsat 5 Image)
(U. S. Geological Survey, 2009)

Strip Number	Image ID	Image Date	Cloud Cover
121-045	LT51210452009011BJC03	2009-01-11	18.02%
122-044	LT51220442009002BJC01	2009-01-02	0.49%

2.2.2 Research steps
The research process follows the steps of generating an LCZ map by using WUDAPT (Bechtel et al., 2015), and is summarized below. Firstly, two Landsat images (listed in Table. 1) were mosaicked, resampled from 30m resolution to 100m resolution, and clipped to fit into the study area. Secondly, around 20 training samples (polygons) for each LCZ class were digitized from Google Earth (Google Corporation, 2016). Building heights and distances between buildings were measured by the ruler provided by Google Earth when selecting samples. A total of 17 types of LCZs were obtained in Hong Kong according to local expertise (Appendix. 1). Lastly, both processed Landsat images and training samples were input into the SAGA GIS software (Böhner and MacCloy, 2006). LCZs were classified by using random forest algorithm. Spectral features contained by training samples were used to build a random forest including a collection of decision trees. A random forest is a prediction model which represents a mapping between attributes of each LCZ class and the identified LCZ type. The forest can be used to classify the whole input image into different LCZ classes.

2.3 GIS-based method
2.3.1 Data
The input data for GIS-based method includes Hong Kong building data, Hong Kong land use data and boundary shapefile in 2009. Building and land use data (including greenery information) of Hong Kong in shapefile format were collected from the Land and Survey Department of Hong Kong. Boundary of the whole Hong Kong territory was collected from the Planning Department of Hong Kong.

2.3.2 Research steps
Detailed actual data of Hong Kong's urban morphology were used to conduct LCZ classification based on the LCZ classification criteria developed by Stewart and Oke (2012). The resolution of GIS mapping was set to be 100 m to facilitate the comparison with the result from the WUDAPT level 0 method. The entire development procedure is shown in Fig. 2.

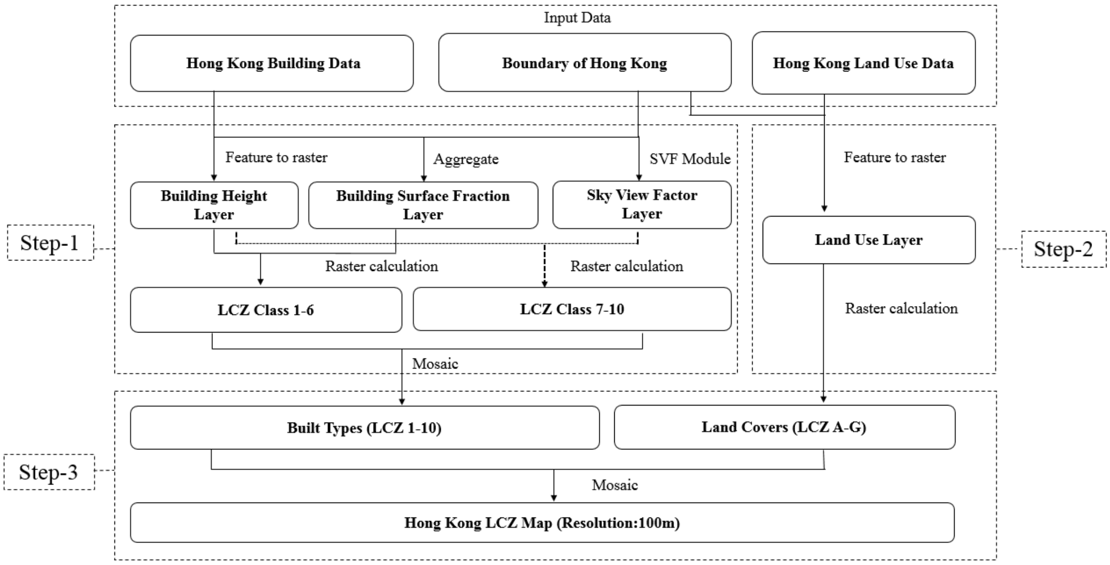

Fig. 2 Workflow of GIS-based Method

Built types (LCZ 1-10) classification: Three layers of contributing factors (building height, building surface fraction, and SVF) were generated from the original input building data with the ArcGIS software (McCoy et al., 2001) with a resolution of 100m. The three layers with 100m resolution were generated by employing functions in the ArcGIS software (Fig. 3a-3c). Next, built types, i.e. LCZ 1-6, were classified according to the building height and building surface fraction layers (Table. 2). Other built types, namely LCZ (7–10), were detected by incorporating the SVF layer with the building height and building surface fraction layers (Table. 2).

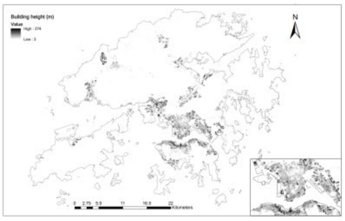

Fig. 3a
Building Height Layer of Hong Kong under GIS-based Method (100m)

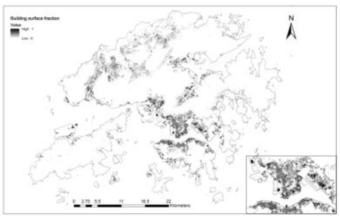

Fig. 3b
Building Surface Fraction Layer of Hong Kong under GIS-based Method (100m)

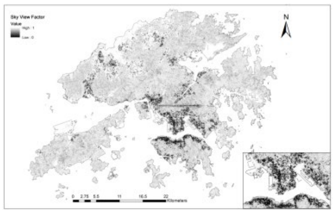

Fig. 3c
Sky View Factor Layer of Hong Kong under GIS-based Method (100m)
(Chen et al., 2012)

*For details, please refer to the online figures.

Table. 2 Classification Parameters of LCZ 1-10 by using GIS-based Method

Built Types	Sky View Factor	Building Surface Fraction (%)	Building Height (m)
LCZ 1-Compact High-rise	N/A	40-60	>25
LCZ 2-Compact Mid-rise	N/A	40-70	10-25
LCZ 3-Compact Low-rise	N/A	40-70	3-10
LCZ 4-Open High-rise	N/A	20-40	>25
LCZ 5-Open Mid-rise	N/A	20-40	10-25
LCZ 6-Open Low-rise	N/A	20-40	3-10
LCZ 7-Lightweight Low-rise	0.2-0.5	60-90	2-4
LCZ 8-Large Low-rise	>0.7	30-50	3-10
LCZ 9-Sparsely Built	>0.8	10-20	3-10
LCZ 10-Heavy Industry	Industrial Type Classified by Hong Kong Land Use Data		

Land cover types (LCZ A-G) classification: For the rural area, a total of six land cover types (LCZ A-G) were further classified basing on the Hong Kong land use type (Table. 3). LCZ A and LCZ B were combined due to the lack of information on wood species.

Table. 3 Classification Parameters of LCZ A-G by using GIS-based Method

Land Cover Types	Hong Kong Land Use Types
LCZ A/B-Dense/ Scattered Trees	Woodland
LCZ C-Bush, Scrub	Shrub Land
LCZ D-Low Plants	Agricultural Land, Grass Land
LCZ E-Bare Rock or Paved	Roads, Railway, Airport, Quarries, Rocky Shore
LCZ F- Bare Soil or Sand	Badland, Vacant Development Land/ Construction in Progress
LCZ G-Water	Reservoirs, Streams, Fish ponds and Nullahs

The LCZ classification map of Hong Kong includes built types (LCZ 1-10) and land cover types (LCZ A-G). They were mosaicked to generate the final LCZ map.

2.4 Accuracy assessment

The accuracy assessment was conducted by manually selecting another independent set of validation samples on the platform of Google Earth. Around ten validation samples were identified for each LCZ class. To assess the classification accuracy of both the GIS-based and WUDAPT methods, confusion matrices were produced by comparing the predicted LCZ maps to those established in the validation samples (Appendix. 2-3). Four indices of classification accuracy were applied in the confusion matrix, including the overall accuracy (OA), the user's accuracy (UA), producer's accuracy (PA) and kappa coefficient. Formulas of OA, UA and PA were presented as follows:

$$\mathrm{UA} = \mathrm{Pd}/\mathrm{P1}$$
$$\mathrm{PA} = \mathrm{Pd}/\mathrm{P2}$$
$$\mathrm{OA} = \sum \mathrm{Pd}/\sum \mathrm{P}$$

Pd: Number of diagonal pixels (correctly classified) of a certain LCZ class

P1: Total number of pixels claimed to be in a certain LCZ class (predicted pixels)

P2: Total number of validation pixels of a certain LCZ class (actual pixels)

$\sum$P: The sum of actual/ predicted pixels, equals to $\sum$ref or $\sum$class.

3. Results and Discussions

3.1 LCZ maps generated by two mapping methods.

Two LCZ maps of Hong Kong were generated using the GIS-based (Fig. 4) and WUDAPT (Fig. 5) methods. For LCZ classification, the WUDAPT method detected all 17 LCZ classes for Hong Kong based on local expert knowledge and selected training samples, while the GIS-based method only detected 15 out of 17 LCZ classes. It is noted that no LCZ 7 (lightweight low-rise) was identified using the GIS-based method. LCZ A (dense trees) and LCZ B (scattered trees) could not be separated by the GIS-based method because of the lack of detailed vegetation information from the collected planning data of Hong Kong.

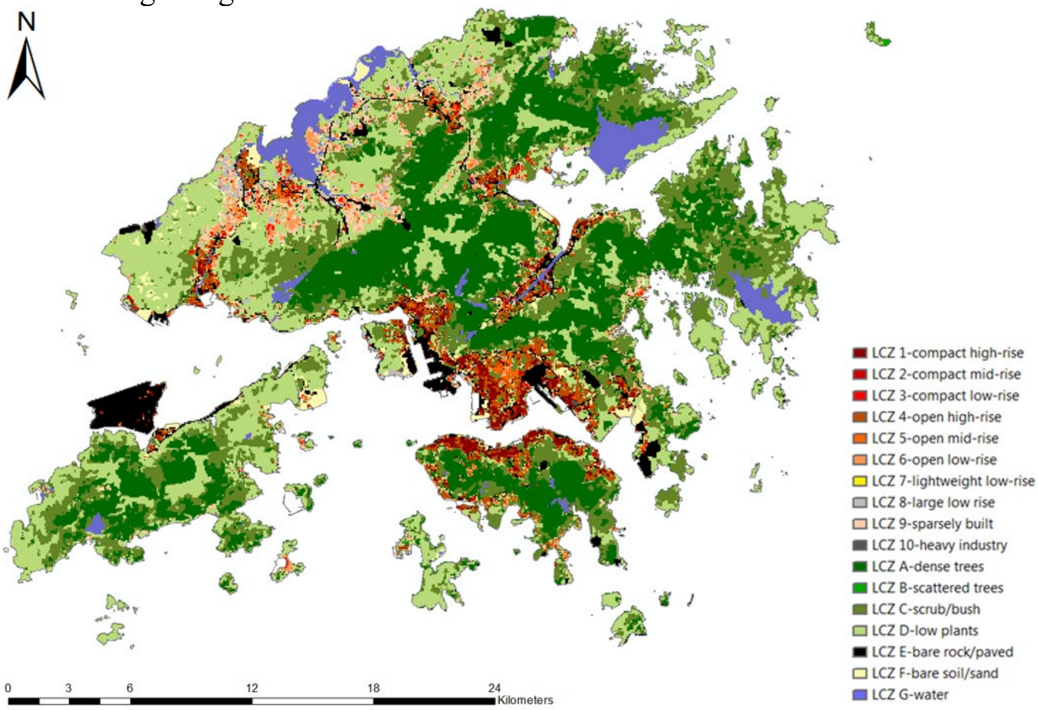

Fig. 4 LCZ Map of Hong Kong Generated by GIS-based Method

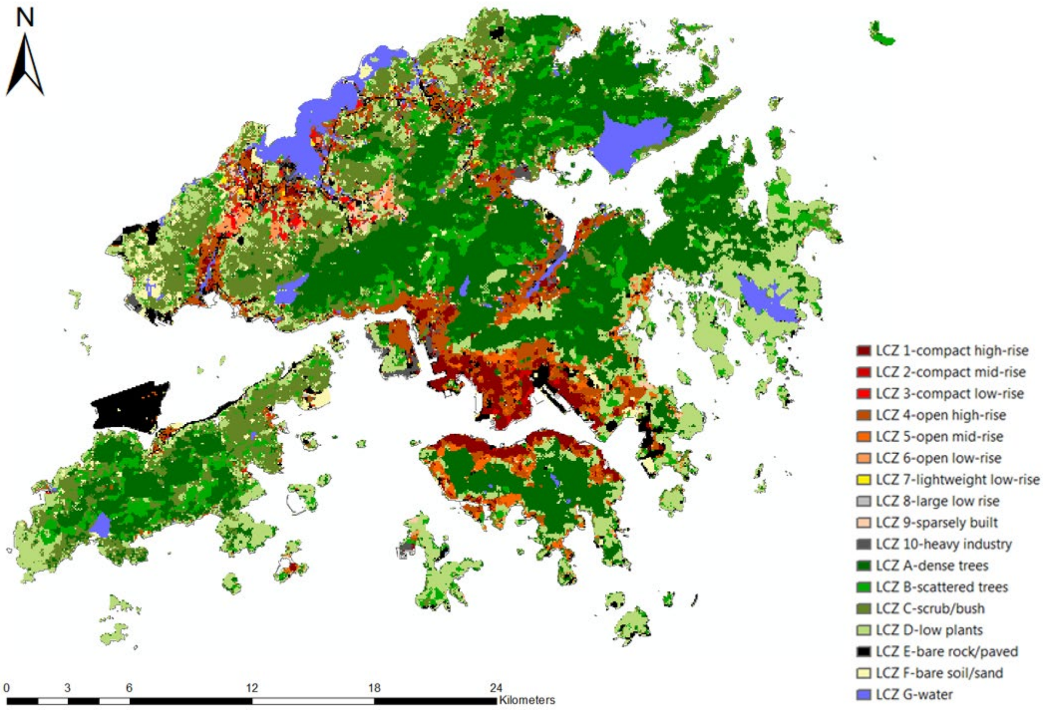

Fig. 5 LCZ Map of Hong Kong Generated by WUDAPT Method

3.2 Accuracy comparison at a city level

A comparison of accuracies of the WUDAPT and GIS-based methods finds that in general the overall accuracy of the GIS-based method was higher than that of the WUDAPT method. The results are shown in the Appendix. 2-3.

It is noted that both LCZ mapping methods can be used to detect the actual spatial pattern of urban morphology and land use in Hong Kong. Firstly, it should be noted that 76% of the total land area are covered by vegetation in Hong Kong (Planning Department of Hong Kong, 2009). Consistent with this, both WUDAPT and GIS-based methods can detect that around 80% of Hong Kong are covered by land cover types of LCZ A-G (Fig. 4, Fig. 5). Next, the two methods identified that the areas of built types are mainly located on the Kowloon peninsula, north of the Hong Kong island and new towns in the New Territories(Fig. 1, Fig. 4, Fig. 5), in line with the actual land use distribution in Hong Kong. Furthermore, both methods successfully distinguished the typical high-density areas in Hong Kong, namely the Kowloon peninsula and northern Hong Kong Island (Fig.1, Fig.4, Fig. 5).

Regarding the overall accuracy, both the WUDAPT and GIS-based methods achieved an accuracy of above 50% according to the accuracy assessments. However, the overall classification accuracy of GIS-based method (72%) is higher than that of the WUDAPT method (58%). Hong Kong is a typical high-density high-rise city with limited land resources, and built types are of particular concern in this study. LCZ 1-6 are the dominate types of built types in Hong Kong. In view of the accuracy of LCZ 1-6, taking both UA and PA into consideration, the GIS-based method performed much better than WUDAPT. GIS-based method differentiates LCZ 1-6 much accurate than WUDAPT method.

The relatively low accuracy of the WUDAPT method, especially in LCZ 1-6, can be explained as follows. One reason is the complicated urban morphology of Hong Kong. Due to its hilly terrain, developable land resources in Hong Kong are scarce. To maximize the development potential and developers' profit, high-density high-rise development and multiple intensive land use are commonly adopted in the urban areas of Hong Kong. Specifically, different kinds of land use – governmental, commercial, residential, and other types – are mixed; buildings with different heights and coverage ratios also coexist. The resulting urban fabric of Hong Kong is intensively mixed. However, LCZ classification simplifies the complex and irregular urban fabric, classifying one area as one dominant LCZ type. Therefore, misclassification occurs mostly in built types. The GIS-based method is relatively more accurate because it classifies built types basing on actual building data to define the parameters of LCZ 1-6 precisely, while the mechanism of WUDAPT method is a kind of machine learning algorithm, depending significantly on the quantity and quality of training samples as well as remote sensing images and local urban morphological characteristics. Therefore, under the unique high-density and complex urban morphology in Hong Kong, the WUDAPT method has a lower overall accuracy than the GIS-based method. It is hard to capture the differences between LCZ 1-6 by using WUDAPT. In addition, a lack of building height information in the Landsat images also leads to the lower accuracy of LCZ 1-6 generated by the WUDAPT method. Xu et al. (2017) assessed the classification accuracy of LCZ map for Guangzhou by using WUDAPT. And the overall accuracy of LCZ 1-6 in Guangzhou is around 60%.

The concept of LCZ is developed based on the simplification and generalization of built types and land cover types of several selected cities (Stewart, 2011), which are not high-density high-rise cities. It is established from general knowledge rather than local expertise, which is especially important in describing the LCZ classes in cities with a unique urban morphology like Hong Kong. Hence, directly adopting the general LCZ concept for Hong Kong LCZ mapping without building data will lead to low classification accuracy. This is another potential reason for the lower accuracy of WUDAPT method.

To analyse the suitability for weather and climate modelling, the results of both the GIS-based and WUDAPT methods as input data for the Weather Research and Forecasting (WRF) model are discussed below. In WRF, the default input land use data is generated by MODIS data with 23-category land use type defined by the U.S. Geological Survey (USGS). However, for urban areas, recent studies tried to analysis their high, mid and low roughness situation (Ren et al., 2017). Thus, LCZ classes were grouped to meet this default land use classification (Appendix. 4). So, built types were re-classified to represent high, mid and low roughness situation (Appendix. 5). Applying the same set of validation samples used for accuracy assessment at a city level, the same accuracy assessment procedure was conducted. Results are shown in Appendix. 6 and Appendix. 7. It is noted that the overall accuracy of the input data over urban classes generated by the WUDAPT method (70 %) is much higher after grouping the original 10 built types into high, mid and low urban categories. Such a result indicates that, when aggregating WUDAPT level 0 data from 100m resolution to 1km resolution, it achieves a higher accuracy. Thus, WUDAPT level 0 data is suitable to be used as input data for WRF model, when GIS data is not available or accessible.

3.3 Accuracy comparison at a district level

Since different districts in Hong Kong follow different development trajectories and have different built forms and morphological characteristics, LCZ mapping accuracies are likely to vary. Therefore, an accuracy assessment at a district level is also conducted for one typical old town and one typical new town. LCZ maps of the selected districts are shown in Appendix. 8.

Following the same accuracy assessment procedure at a city scale, the results of the accuracy comparison between the GIS-based method and the WUDAPT method at a district level are shown in Table. 4. New validation samples in each district were selected from Google Earth.

Table. 4 Accuracy Comparison of Two LCZ Mapping Methods in Selected Districts

District	Description	GIS-based Method		WUDAPT Method	
Kowloon	Percentage of Main Built Types (%)	LCZ 1	14.86	LCZ 1	30.03
		LCZ 4	17.54	LCZ 4	24.86
		LCZ 5	7.67	LCZ 5	9.37
	OA of Built Types (%)	49		39	
	UA of Main Built Types	LCZ 1	0.50	LCZ 1	0.33
		LCZ 4	0.61	LCZ 4	0.52
		LCZ 5	0.63	LCZ 5	0.62
	PA of Main Built Types	LCZ 1	0.67	LCZ 1	0.79
		LCZ 4	0.40	LCZ 4	0.29
		LCZ 5	0.59	LCZ 5	0.47
Yuen Long	Percentage of Main Built Types (%)	LCZ 5	1.54	LCZ 5	0.53
		LCZ 6	7.75	LCZ 6	3.40
		LCZ 9	10.77	LCZ 9	3.04
	OA of Built Types (%)	37		12	
	UA of Main Built Types	LCZ 5	0.50	LCZ 5	0.67
		LCZ 6	0.33	LCZ 6	0.12
		LCZ 9	0.43	LCZ 9	0.50
	PA of Main Built Types	LCZ 5	0.75	LCZ 5	0.17
		LCZ 6	0.50	LCZ 6	0.14
		LCZ 9	0.46	LCZ 9	0.08

3.3.1 Selected old town

Kowloon is one of the early developed downtown areas in Hong Kong. Buildings with different ages and forms are distributed disorderly in this district, so its urban morphology is complicated. LCZ 1 and LCZ 4 should be the main built types in this area.

The overall accuracy of built types by using GIS-based method is 10% higher than that of the WUDAPT method from the quantitative perspective. And it detects much more urban details than WUDAPT from the perspective of local expertise. However, the WUDAPT method detects little differences in LCZ classes; its LCZ classification map shows a more homogenous pattern. The number of grids classified as LCZ 1 by WUDAPT method is significantly greater than that of the GIS-based method, although LCZ 1, LCZ 4 and LCZ 5 still cover the main parts of Kowloon. The WUDAPT method is not able to depict the true situation in Kowloon, which, from the perspective of local expert knowledge, consists of mixed building types rather than a homogenously large area of LCZ 1. In addition, when looking into the individual accuracy of each LCZ class, taking UA and PA into account, the classification accuracies of LCZ 1, LCZ 4 and LCZ 5 by using the GIS-based method are all higher than that of the WUDAPT method. GIS-based method detects differences in built types more accurately than WUDAPT.

3.3.2 Selected new town

Yuen Long new town was first developed in 1977 (Hills and Yeh, 1983). It is located in the middle of a plain, convenient for construction and planning. Yuen Long was a typical rural area with a lot of agriculture lands before its new town development. At the centre of Yuen Long, there are mainly public housing buildings with some open spaces. Surroundings are of low-rise house types. LCZ 5, LCZ 6 and LCZ 9 are the major built types in Yuen Long.

In the LCZ map produced by the GIS-based method, LCZ 5, LCZ 6 and LCZ 9 are the main built types; but WUDAPT detects less area of actual main built types in Yuen Long. Therefore, the GIS-based method captures the main dominating LCZ type much better than WUDAPT. The overall accuracy of built types by using the GIS-based method is 25% higher than that of the WUDAPT method. The GIS-based method differentiates the main built types more accurately than WUDAPT.

3.4 Advantages and limitations

3.4.1. Representation of urban morphology

A few points can be summarised following the comparison of the classification performance of the two LCZ mapping methods at both the city and district scales. Firstly, both methods can detect the different LCZ classes, which is consistent with the actual spatial distribution of land use in Hong Kong. However, the GIS-based method has a higher accuracy rate than WUDAPT method, especially for LCZ 1-6.

Apart from the higher overall accuracy of the GIS-based method, it detects individual LCZ classes with relatively high accuracies, according to both user's accuracy and producer's accuracy. The GIS-based method performs better than the WUDAPT method at both the city and district scale. Especially at the district scale, the GIS-based method classifies dominate built types much more accurately than WUDAPT. Around half of dominate built types in the selected districts are classified correctly when applying the GIS-based method. Therefore, the GIS-based method is better when detailed analyses are conducted.

The WUDAPT method generates LCZ maps with a more homogeneous pattern than the GIS-based method. This is because the training samples used in the WUDAPT method are usually larger than sizes of building blocks in Hong Kong. Since the selected training samples are from collected remote sensing images, they only contain spectral information without detailed building height information. That is why the statistics of building height generated from WUDAPT level 0 data for Hong Kong (Ren et al., 2016) is not as accurate as the result generated by the GIS-based method. The WUDAPT method has an overall accuracy of 58%, indicating that it can be used when precise urban morphology data in GIS format are lacking. However, the accuracy of this method is less satisfactory when specific LCZ classes need to be examined thoroughly. This method may not be so helpful for researchers hoping to look into details at a district level.

In addition, according to the qualitative description of the two LCZ maps, the WUDAPT method can differentiate land cover types better, especially for the greenery part, since satellite images contain more detailed information on vegetation. However, the GIS-based method is based on land use maps at zoning level and with less greenery details.

3.4.2 Mesoscale weather and climate modelling

For mesoscale weather and climate models, such as WRF, input data including land use and urban morphological data are required at 1 km resolution. Therefore, WUDAPT level 0 data can be used, especially for developing countries or regions where land use information is not readily available or accessible (Brousse et al., 2016; Ren et al., 2017).

3.4.3. LCZ map updating and management

Due to the rapid urban development and new town construction, especially in developing countries and regions, there is a need to update LCZ classification results to meet new needs that arise in line with new developments. Since the WUDAPT method employs satellite images, it is easier for planners and government officials to update and manage LCZ maps, compared to the GIS-based method.

4. Conclusion

Local Climate Zone has become an international standard method to explore urban morphology and its impact on local temperature. GIS-based and WUDAPT methods are the two most popular ways to classify and to map LCZs. This study uses Hong Kong's high-density complex urban areas to examine both methods' performance and accuracy. It is found that at a city level, GIS-based method has a better accuracy rate than WUDAPT, but the general spatial distribution patterns of different LCZ classes in these two LCZ maps both match with the reality of Hong Kong. When the results from each method were aggregated from 100m resolution to 1km resolution, it is found that the WUDAPT method has achieved an acceptably high accuracy of urban categories. Thus, WUDAPT level 0 data are suitable as input data for mesoscale weather and climate modelling, such as WRF, at a coarse spatial resolution of 1km. Under such circumstances, WUDAPT's advantages of freely accessible data, simple methodology, and suitable accuracy for application will be helpful for researchers, especially those in developing countries and regions where GIS data is either not available or not complete. The findings on suitability and limitation of both methods can provide a useful reference for researchers who are interested in LCZ classification and mapping work for their cities. And the results of urban morphology analysis can also be referred to by local planners and designers for a better understanding of urban morphological characteristics in high-density urban areas. They can also assist their design work.

The current relatively low accuracies of the WUDAPT method in built types of LCZ echo the findings in previous studies in other high density cities, such as Guangzhou, Shanghai, Hangzhou in China and San Francisco in US (Xu, et al, 2017; Cai, et al, 2017; Li, 2017). On the one hand, further improvements can be made in the future by adopting high-resolution remote sensing images or conducting remote sensing image fusion to improve the quality of output of LCZ classification and mapping; on the other hand, sub-classes of built types of LCZ should be considered to capture the variation of each LCZ in high density urban areas.

The study's results on land cover types of LCZ are relatively accurate. But for the GIS-based method, conducting remote sensing image fusion can help improve its output quality. In general, information of greenery and vegetation extracted from the land cover types of LCZ may be helpful in ecology or landscape related studies.

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Appendix

Appendix. 1 Snapshots of LCZ Training Samples for Hong Kong from Google Earth

LCZ 1 Compact High-rise

LCZ 2 Compact Mid-rise

LCZ 3 Compact Low-rise

LCZ 4 Open High-rise

LCZ 5 Open Mid-rise

LCZ 6 Open Low-rise

LCZ 7 Lightweight low-rise

LCZ 8 Large low-rise

LCZ 9 Sparsely built

LCZ 10 Heavy industry

LCZ A Dense trees

LCZ B Scattered trees

LCZ C Bush, scrub

LCZ D Low plants

LCZ E Bare rock or paved

LCZ F Bare soil or sand

LCZ G Water

Appendix. 2 Accuracy Assessment Result of LCZ Map Generated by GIS-based Method

LCZ	1	2	3	4	5	6	7	8	9	10	A	B	C	D	E	F	G	∑ref	PA
1	58			9	2					1			1	2		1		74	.78
2	12	34		2	6				1						1			56	.61
3			24			16			5					1				46	.52
4	3	2		97	2	1							3	0	3			111	.87
5	3	16		5	69				1		1		2	1	4	1		103	.67
6			3		3	77		1	9									93	.83
7						3	0											3	.00
8			3		1	5		0							1			10	.00
9						18		2	90				3	7	5			125	.72
10					1	1				3				2				7	.43
A											94							94	1.0
B	1	2		11	1			1			11	0	37	26		2		92	.00
C													102	30				132	.77
D						1		1	1				9	48				60	.80
E					1			5	1					1	72	21		101	.71
F													1	15	12	73	1	102	.72
G																	110	110	1.0
∑class	77	54	30	124	86	122	0	10	108	4	106	0	158	133	98	98	111	Kappa: 0.70	
UA	.75	.63	.80	.78	.80	.63	-	.00	.83	.75	.89	-	.65	.36	.73	.74	.99	OA (%): 72	

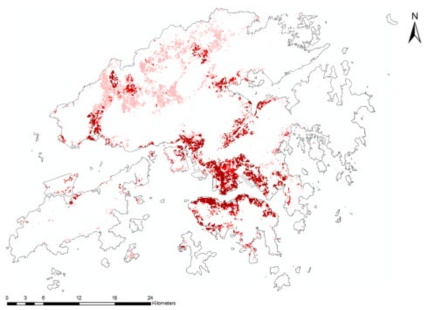
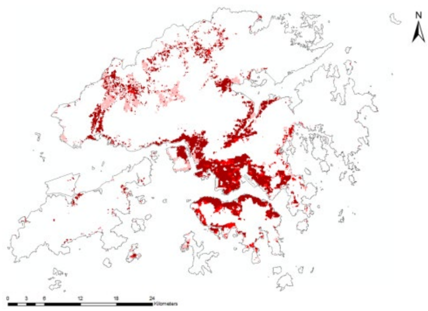
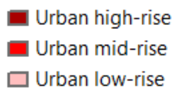
Appendix. 3 Accuracy Assessment Result of LCZ Map Generated by WUDAPT Method

LCZ	1	2	3	4	5	6	7	8	9	10	A	B	C	D	E	F	G	∑ref	PA
1	71	1		1	1													74	.96
2	21	18		11	1							2			3			56	.32
3			13	6		20				1			2	3	1			46	.28
4	8	1		95						2					3		1	110	.86
5	21	16		31	20	3	2			1	1		1		6		1	103	.19
6	1		29	11	2	29	7		3	7				2	2			93	.31
7	1					1	0					1						3	.00
8	1		4	1				1	3	2					1			13	.08
9	1		6	30		8			45	7			7	11	10			125	.36
10	3									1				3				7	.14
A											94							94	1.0
B				15							5	37	25	9		1		92	.40
C											29	15	80	6		2		132	.61
D				2								1	28	29				60	.48
E	2			3	1										93	6		105	.89
F				5								9	16	3	15	48	7	103	.47
G	2										6		3	1		2	96	110	.87
∑class	132	36	52	211	25	61	9	1	51	21	135	65	162	67	134	59	105	Kappa: 0.55	
UA	.54	.50	.25	.45	.80	.48	.00	1.0	.88	.05	.70	.57	.49	.43	.69	.81	.91	OA (%): 58	

Appendix. 4 Conversion between Local Climate Zone Classes and USGS Land Use Categories

	LCZ Category	USGS Land Use Categories
Built Types	LCZ 1 LCZ 4	Urban High-rise
	LCZ 2 LCZ 5	Urban Mid-rise
	LCZ 3 LCZ 6 LCZ 7 LCZ 8 LCZ 9 LCZ 10	Urban Low-rise
Land Cover Types	LCZ A LCZ B	Mixed Forest
	LCZ C	Shrub Land
	LCZ D	Cropland/Grassland Mosaic
	LCZ E LCZ F	Barren or Sparsely Vegetated
	LCZ G	Water Bodies

Appendix. 5 Spatial Distribution of Input Urban Data for WRF Model via Two LCZ Mapping Methods

GIS-based Method	WUDAPT Method	Legend
		

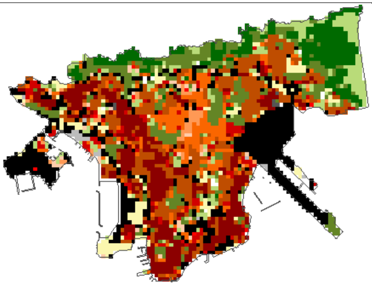
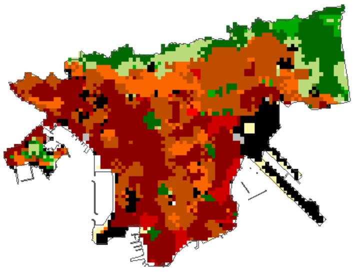
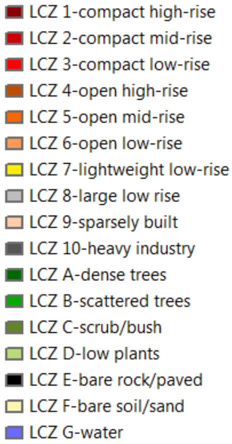
Appendix. 6 Accuracy Assessment of Built Type Data for WRF Model Generated by GIS-based Method

Urban Categories	Urban High-rise	Urban Mid-rise	Urban Low-rise	∑ref	PA
Urban High-rise	125	6	4	135	.93
Urban Mid-rise	18	112	5	135	.83
Urban Low rise		4	137	141	.97
∑class	143	122	146	Kappa: 0.86	
UA	.87	.92	.94	OA (%): 91	

Appendix. 7 Accuracy Assessment of Built Type Data for WRF Model Generated by WUDAPT Method

Urban Categories	Urban High-rise	Urban Mid-rise	Urban Low-rise	∑ref	PA
Urban High-rise	139	2	1	142	0.98
Urban Mid-rise	83	48	7	138	0.35
Urban Low rise	29	0	97	126	0.77
∑class	251	50	105	Kappa: 0.55	
UA	0.55	0.96	0.92	OA (%): 70	

Appendix. 8 LCZ Maps Developed by GIS-based Method and WUDAPT Method for Selected Districts

LCZ Map Developed by GIS-based Method	LCZ Map Developed by WUDAPT Method	Legend of LCZs
Kowloon		
		
Yuen Long