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Local Climate Zone Mapping for Energy Resilience: A Fine-grained and 3D Approach

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Abstract

The LCZs (Local Climate Zones) system and its mapping have been emerging in recent years as an important approach to study the variations of local climates in cities, which are closely linked to human comfort issues and building energy demand. However, most of the current practices of LCZs mapping are based on 2D satellite images that can only provide rough estimations. This study tries to improve the current LCZs mapping methods by proposing a bottom-up method that adopts high-resolution 3D building data, land cover data, land use data, etc. This fine-grained and 3D LCZs mapping method has three advantages: using urban block unit as the basic spatial unit to derive more reasonable LCZs; bridging the real urban form with urban canyon models to provide more appropriate parameters; and adopting the linear interpolation algorithm to improve the current LCZs classification system. The mapping method has been tested in Manhattan, Atlanta and central Tokyo, and the results show distinctive LCZ types and distribution patterns in these three cities. This method can be used to provide more accurate LCZs maps that help to better understand human comfort and simulate urban-scale building energy performance, which could inform urban designers and policy makers on the UHI mitigation strategies and urban redevelopment strategies.

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Keywords: Urban Heat Island (UHI); Local Climate Zones (LCZs); urban form; urban canyon; GIS; urban block unit

1. Introduction

The Urban Heat Island (UHI) effect, a term first coined in the 1940s, has been recognized as a more and more serious environmental issue in cities[1]. It was often shown as elevated temperatures of largely

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urbanized areas comparing to rural areas in the same region [2]. The changing temperatures caused by the UHI effect lead to different human comfort levels and air qualities, which relate to human health, as well as cooling demands in buildings [1, 3, 4]. Its main causes are believed to relate to three characteristics of cities: increased roughness due to building geometries, drier and more impervious surfaces and anthropogenic heat and moisture releases [1, 5, 6].

Although there has been tremendous amounts of research on the UHI effect, including empirical studies and modeling developments [6, 7], findings have limited capabilities to inform policy making to mitigate the UHI effect. One reason is the spatial unit of analysis. Most of the current studies focused on local climates of particular case areas, or on the general climatic differences between the "urban" and "rural". However, to understand how a city performs in terms of the UHI effect, individual urban areas or the dichotomy of urban-rural are far from enough because different urban forms in the same city may have quite distinctive local climate conditions. Oke and Steward proposed a detailed classification system for urban form to improve the UHI studies. They categorized urban areas into "local climate zones", regions of homogenous surface cover, material, structure and human activity with the area radius of hundreds of meters to a few kilometers [1]. The 17 basic LCZs types are shown in Fig 1.

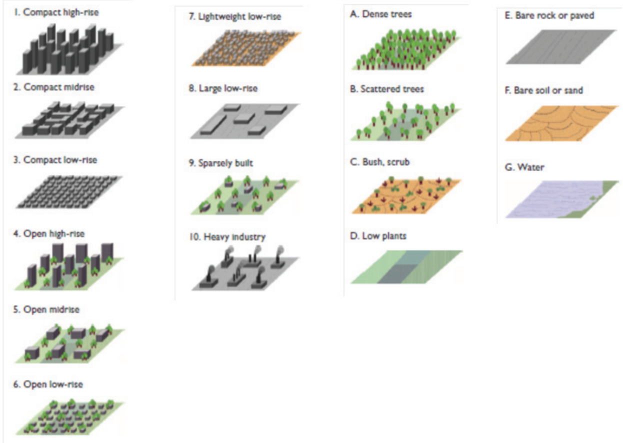

Fig. 1. 17 LCZs types with 10 as built types and 7 as land cover types [1]

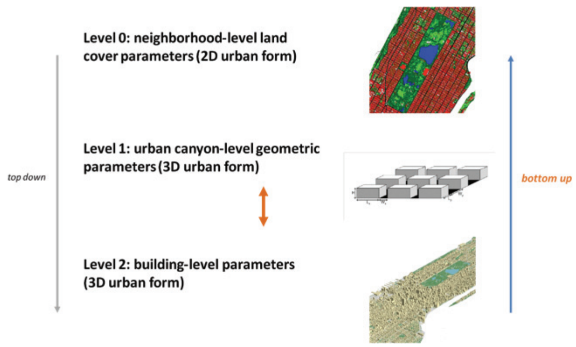

Fig. 2. Three levels of LCZ mapping methods (summarized based on the concepts in Mills et al's paper [8])

The World Urban Database and Portal Tool (WUDAPT), an internationally collaborated project on climatic data management and dissemination, adopts the LCZs as a main method for spatial climatic data management and studies [8]. Although LCZs maps were produced for more than 90 cities in WUDAPT [9], they generally followed the method of Bechtel et al, which uses remote sensing to classify the urban domain into neighborhood typologies using the definition of LCZs [10]. However, such a method is based on the two dimensional urban form and landscape pattern, which is limited in getting the parameters of the urban canyon geometry and building function that determine the local climate [6]. Mills et. al. called this approach the "level 0" method, and proposed "level 1" and "level 2" methods that use more detailed data [8], as shown in Fig 2. But in current practices of LCZs mapping, very few focused on levels above 0. This paper tries to fill this gap by proposing and testing a fine-grained and three dimensional bottom-up approach for generating LCZs mappings to go from "level 0" to "level 2" by considering the complex 3D urban form and its relationship with the underlined urban canyon model in the LCZs classification.

2. Methodology

The proposed bottom up approach uses urban block unit as its basic spatial unit to organize 3D detailed urban form information such as building and land cover data, bridges the complex urban form with urban canyon models that are widely used in urban climatology studies, and improves upon the current LCZs classification method.

2.1. Urban block unit and block level parameters

The urban block as a spatial unit is naturally defined by the streets. When its boundary is enlarged to include the streets, it becomes an ideal basic spatial unit to study the relationship between buildings, spaces in between and the land covers, which determine the local climate. The enlarged urban block is defined as the "urban block unit" whose boundaries are street centerlines. Once the LCZ type of each urban block unit is identified by its parameters, the clustering method can be used to define the area of each continuous LCZ. The minimum area has a 200-500 m required radius to avoid its transitional area totally overlapping with surrounding LCZs of different kinds [1]. The detailed building data, land cover data and land use data, often have different spatial units when organized in the GIS format and therefore need to be aggregated at the block level.

The urban block unit is generated in GIS by dividing the whole urban area with the street centerlines, or using the census group boundary as the approximation. The generation of block level parameters is also done in GIS with the dissolve tool, the clip tool and spatial join tool, as well as other spatial operational tools depending on the spatial unit of the original data.

2.2. Complex urban form and the urban canyon model

The parameters defining the LCZ are based on the urban canyon model including the H/W ratio, cover ratio, vegetation cover ratio and building height [1]. As the urban canyon model is a simplified urban form, its parameters need to be calculated from the parameters of the real urban environment. In current physically based local climate modeling research, such calculations are based on greatly simplified algorithms [7, 11], which are problematic because they ignore the overlapping of the urban canyon spaces in urban grid with two perpendicular sets of urban canyon systems (Fig 3). They are also problematic due to a lack of consideration of courtyard building types.

Therefore an improved method is used to provide the parameters based on the urban canyon model. The building shapes in real urban environment are transformed to the ideal urban grid model by transforming the courtyard buildings into equivalent buildings without courtyards (Fig 4) and by assuming an equivalent urban form with the same cover ratio and perimeters, etc, instead of the method in the literature that only considers the cover ratio.

The parameter transforming can be done in GIS using the attribute calculation tool, dissolve tool, etc.

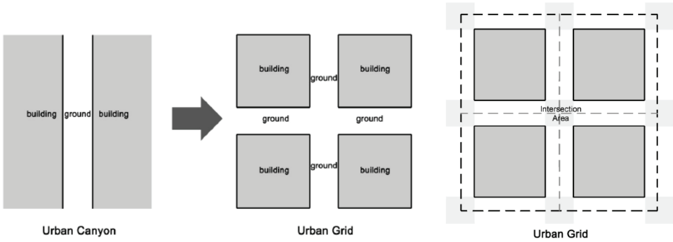

Fig. 3. From urban canyon model to urban grid model with two sets of perpendicular urban canyon systems

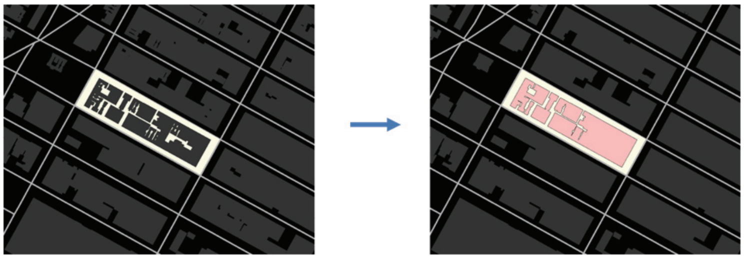

Fig. 4. Courtyard buildings and their equivalent buildings for generating parameters based on the urban canyon model

2.3. Improved LCZs classification method

Stewart and Oke's LCZs classification method, however, shows its limitations after scrutinizing the above problems. While each LCZ has its own ranges of different parameters for identification, there are some overlapping scenarios and all of the LCZs cannot cover the whole design space of those parameters. This sometimes causes difficulties in classifying actual urban landscape patterns based on the current LCZ parameters.

To solve this problem, a multi-dimensional linear interpolation method is used to find the closest LCZ type as the dominant one, and if possible the second closest one as the secondary for each possible urban form in cities based on the LCZs classification method from Steward and Oke [1]. The improved LCZs classification can be done in Excel or GIS using the linear interpolation algorithm on Steward and Oke's LCZs classification.

The new LCZ mapping system with the above four methods uses building scale "level 2" data as inputs and classifies the urban area into LCZs by scaling up and transforming the data. It has advantages over the previous "level 0" method including considering the 3D urban environment and bridging the complex real urban form with the simplified urban canyon model, which provides the basis for the LCZ classification system.

3. Case studies

The proposed LCZ mapping method is applied to three case urban areas, Manhattan, Atlanta and Tokyo (central area), for testing the proposed method. For each city, the building footprints, streets, land use and land cover data are collected in GIS format, and the LANDSAT data are also used for Manhattan and Atlanta since the data source only covers US cities. Based on those data, the urban block units are generated and the basic block-level LCZ parameters are calculated (Fig 5).

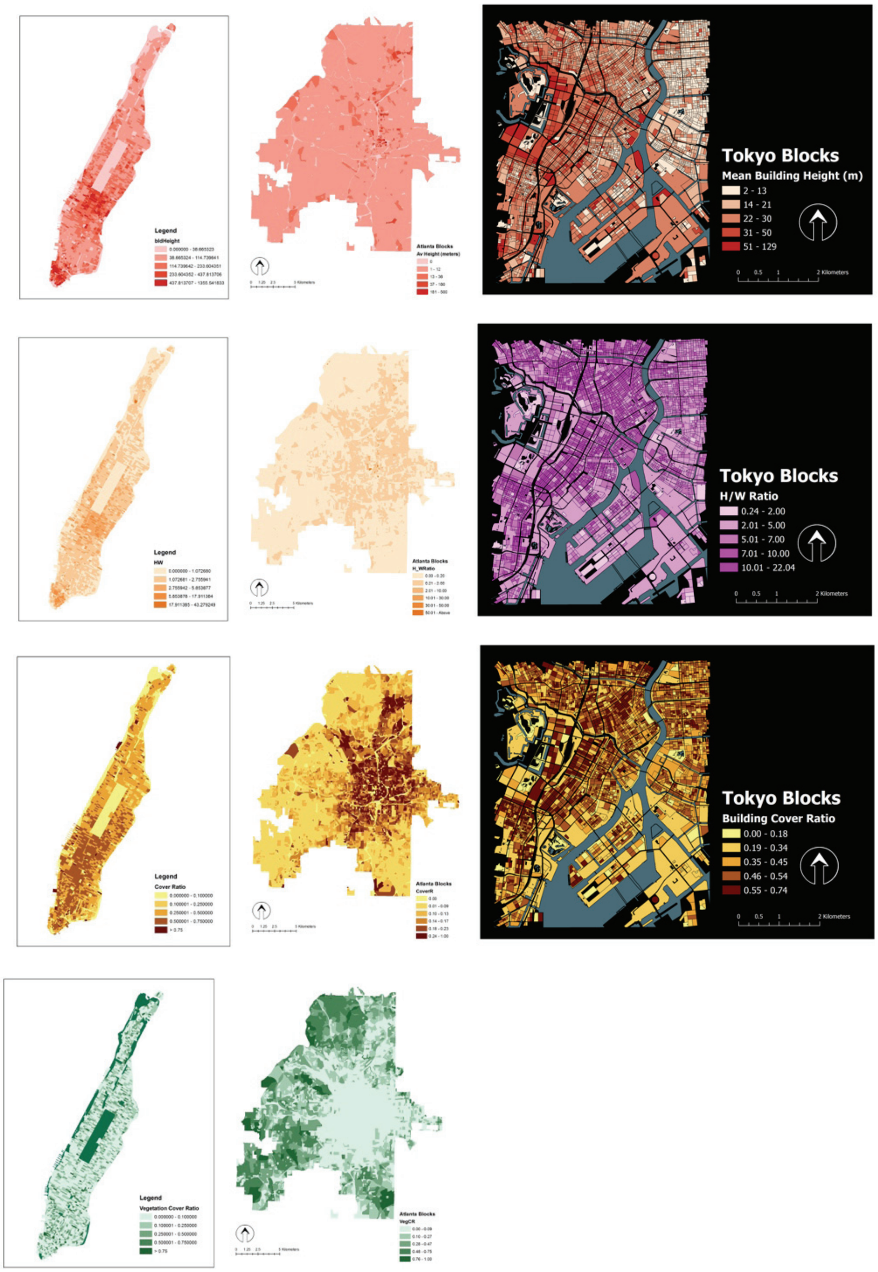

Fig. 5. Block level urban canyon parameters in three case studies

From left to right: Manhattan, the City of Atlanta and the central Tokyo; from top to down: Average building height, H/W ratio, cover ratio and vegetation cover ratio (Tokyo vegetation cover mapping is missing because of unavailability of the LANDSAT data)

Using the improved classification method, LCZ maps are produced for the three test case cities, as shown in Fig 6. It is obvious that different cities have their distinctive dominant LCZ types or urban form patterns. In Manhattan, a majority of the LCZs are the compact high-rise LCZ. In Atlanta the dominant LCZs are the compact high-rise and open low-rise. In central Tokyo, there are a large number of block units that belong to the compact mid-rise LCZ type. The distinctive urban forms among the three cities resulted from complex historical processes in different social, economic, cultural and regulatory contexts. The LCZ maps can be further used to study outdoor human comfort, or in urban energy modeling to estimate the building energy consumptions.

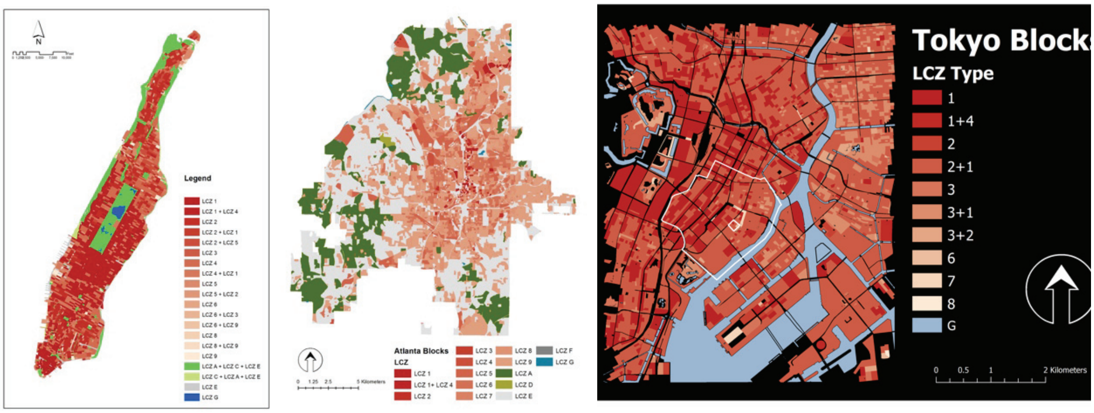

Fig. 6. LCZs mappings for Manhattan (left), Atlanta (middle) and central Tokyo (right)

4. Conclusions

The LCZs classification system and its mapping technique have been an emerging important approach to study the variations of local climates in cities, which are closely tied to human comfort and building energy demand. However, the current practice of LCZ mapping proposed by WUDAPT uses mostly a low-resolution estimation method based on 2D urban patterns. In order to better reflect the local climate distributions in the urban domain, this study proposed a finer-grain LCZs mapping approach that adopts high-resolution building data with 3D information, land cover data, parcel data, etc. to define the LCZs, moving forward from the "level 0" to the "level 2" [8].

The proposed fine-grained and 3D LCZs mapping method has three advantages. First, it uses urban block unit, a naturally defined basic unit in cities, as its spatial unit for defining the LCZ type, and clusters the block units based on LCZ type and spatial neighboring relations to form final LCZs. By doing so, the urban structure defined by streets and the urban form patterns in a block are both considered and integrated in the mapping. Second, it considers the complex urban form and its simplified representation as urban canyon models in the urban climatology studies. By bridging the real urban settings and simplified urban canyon models, this method provides the parameters that are closer to the LCZ classification systems defined by Stewart and Oke [1]. Third, it enhances the current LCZs classification method, which contains overlapping scenarios and cannot cover the whole design space. By introducing the linear interpolation algorithm, this method fills the gap and further advances the LCZs classification system.

The proposed LCZs mapping method was applied to three urban areas: Manhattan, Atlanta and central Tokyo. Despite the data availability issue, the results show distinctive LCZ types and distribution patterns in the three cities. The results of LCZ mapping can be used to better understand the relationship between urban form and outdoor human comfort, and could be integrated in urban building energy modeling to simulate building energy performance [12]. It could inform urban designers and policy makers on UHI mitigation strategies and urban redevelopment decisions at the urban scale.

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