Theoretical and Applied Climatology (2019) 137:2657–2662
https://doi.org/10.1007/s00704-018-02764-x

ORIGINAL PAPER

Interpreting air temperature generated from urban climatic map by urban morphology in Taipei

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Received: 18 April 2018 / Accepted: 28 December 2018 / Published online: 12 January 2019
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Abstract
The intense development of Taipei City has caused high thermal stress in its urban areas. This study used the urban climatic map (UCmap) and the local climate zone (LCZ) to analyze how land development patterns have affected urban thermal conditions. The UCmap is an efficient tool for obtaining information about urban microclimatic conditions based on urban development parameters and the map provides urban planners with information to mitigate the growing problem of thermal stress. The LCZ is system for classifying urban morphology including land cover, buildings, and vegetation, which can be used to relate land patterns to climate conditions. The results of this study indicate that combining UCmap and the LCZ is helpful for assessing thermal conditions in urban areas, and this approach can be used in many cities to determine the most suitable built environment for mitigating thermal stress.

1 Introduction

Thermal conditions in cities change considerably during urbanization due to the reduction of green areas and the development of buildings (Kent 2011; Ongoma et al. 2016). Urbanization is a long-term global trend that causes the urban heat island (UHI) phenomenon in many cities (Oke 1973). Understanding how land morphology affects thermal conditions is critical to governments to determine strategies for mitigating thermal stress caused by urban development.

Studies have used several urban environmental and developmental parameters to evaluate thermal conditions in urban areas, including land use, population, total floor area (TFA), impermeable surface ratio (IMP), building coverage ratio (BCR) and green area ratio (GCR) (Chang et al. 2010; Merbitz et al. 2012; Honjo et al. 2015). These studies have confirmed that land development patterns affect microclimates (Lu et al. 2012; Kotharkar and Surawar 2015; Shih 2017).

The urban climatic map (UCmap) integrates urban development parameters and quantifies the intensity of urban development to investigate the relationship between urban development and thermal conditions in cities (Ren et al. 2010; Chen et al. 2016a, b; Lin et al. 2017). The UCmap helps urban planners and architects to identify and visualize hot spots where meteorological data is unavailable, and it offer guidance for decision about legislation concerning thermal condition (Ng and Ren 2015).

Several methods have been applied to identify hot spots using the UCmap (Wong et al. 2010; Ren et al. 2012); however, three problems are associated with these methods. The first is that some cities may lack access to information, posing an obstacle to the study of the relationships between urban development patterns and thermal environments. The second problem is that mixed land use in cites makes it difficult to investigate the relationship between urban environments and thermal conditions. Third, the use of the UCmap was based on previous approaches (Chen et al. 2016a, b; Lin et al. 2017) that require rigorous local measurement; such approaches are not feasible to cities with inadequate meteorological stations and/or instruments. For these reasons, this study used the local climate zone (LCZ), a land morphology classification system developed by (Stewart and Oke 2012; Stewart et al. 2013). LCZ categorizes land development patterns from satellite

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imagery to analyze land morphology and its relationship with UCmap. By mapping LCZs, urban characteristics and thermal conditions in the study area were comprehensively described (Bechtel et al. 2015; Cai et al. 2016; Kaloustian and Bechtel 2016).

2 Method

2.1 Study area

Taipei City (25° N, 121° E) is located in the Taipei Basin in northern Taiwan. The urbanized area covers approximately 2726 km^2 and has an estimated population of 6.67 million. Taipei has a monsoon-influenced humid subtropical climate. According to the Central Weather Bureau, the annual average air temperature (Ta) in Taipei City from 1981 to 2010 was 23 °C. The warmest month is July (29.6 °C) and the coolest month is January (16.1 °C).

2.2 Establishment of an urban climatic map

2.2.1 Collection of urban development layers

Four urban layers were employed in this study—namely IMP, TFA, BCR, and GCR—to develop a UCmap (Fig. 1). The IMP data were obtained from the Spot-6 satellite, which gathers information on land cover and urban development (Lin et al. 2005). A higher IMP indicates a greater surface area of non-natural features, which contribute to higher temperatures (Frazer 2005; Xiao et al. 2007). The TFA and BCR data were obtained using a digital building model, which reflected the characteristics of the built environments. Regions with higher TFA values indicated a greater population and higher anthropogenic heat. Finally, GCR data were interpreted from land use data; all areas with vegetation, such as forests, parks, and farmland, were regarded as green spaces. Higher GCR values correspond with larger green areas that mitigate high temperature. All of the layers were imported into the Quantum Geographic Information System for spatial analysis and for visualizing urban develop characteristics in the study area.

2.2.2 Traverse measurement

A mobile meteorological measurement was taken on August 8, 2017 to obtain the Ta data around the study area (Fig. 2). The methods of measurement were based on other UCmaps for Tainan and Taichung (Chen et al. 2016a, b; Lin et al. 2017). A small passenger car was equipped with a GPS recorder (GT-820) and meteorological sensors to measure Ta and relative humidity (Delta OHM5 DO9847). It can provide data on thermal conditions in various urban districts. The precision of the instruments was ± 0.5 °C for the air thermometer used and ± 2% for the relative humidity meter with both instruments recording at time intervals of 5 s.

To connect the thermal conditions data with the urban development layers, the Ta data and the geographic coordinates were linked by time alignment, and these data were then linked with the urban development layers using the space alignment method.

2.2.3 Estimation model for mapping the urban climatic map

The urban development information and mobile measurement data were integrated to construct the estimation model for the UCmap (Chen et al. 2016a, b; Lin et al. 2017). Data on the thermal conditions revealed significant differences in areas corresponding to different intensities of development in the study area. Therefore, the following multiple linear regression analysis was adopted to quantify the effect of each layer and to understand how thermal conditions contributed to the deviations:

$$\mathrm{TA_i} = f(\mathrm{TA_{station}}, \mathrm{IMP_i}, \mathrm{BCR_i}, \mathrm{GCR_i}, \mathrm{TFA_i}, \mathrm{ELV_i}) \quad (1)$$

In Eq. 1, $\mathrm{TA_i}$ is the real air temperature value in each grid$_i$ obtained from the measurement. $\mathrm{TA_{station}}$ represents the Ta data obtained from the central weather station in Taipei City, and these data were used as a reference for constructing this estimation model. $\mathrm{IMP_i}$, $\mathrm{BCR_i}$, $\mathrm{GCR_i}$, and $\mathrm{TFA_i}$ refer to the intensity of urban development in each grid$_i$. Elevation$_\mathrm{i}$ is the elevation of each grid$_\mathrm{i}$. The selected parameters depend on the p values with a 90% confidence interval. The thermal conditions of each city can be conveniently estimated using this model.

2.3 Mapping local climate zone

The LCZ classification system was also employed to map land development patterns into related climatological zones (Stewart and Oke 2012). This approach defines land development patterns according to the thermal admittance of materials; surface cover around roughness features; structural properties of buildings and vegetation, such as type, height, and density; and types of land cover. To achieve this mapping, the study obtained images from the LANDSAT 8 satellite included in the United States Geological Survey of 16 August, 2016, and the study followed instructions in the World Urban Database and Access Portal Tools using SAGA GIS (2.2.0) to generate LCZ distribution map of Taipei City with a 100-m resolution.

3 Results

3.1 Air temperature distribution map

The Ta distribution map which is constructed using the estimation model, showed that the Ta differences were up to 6 °C at temperature of 28 °C to 34 °C in August during the daytime

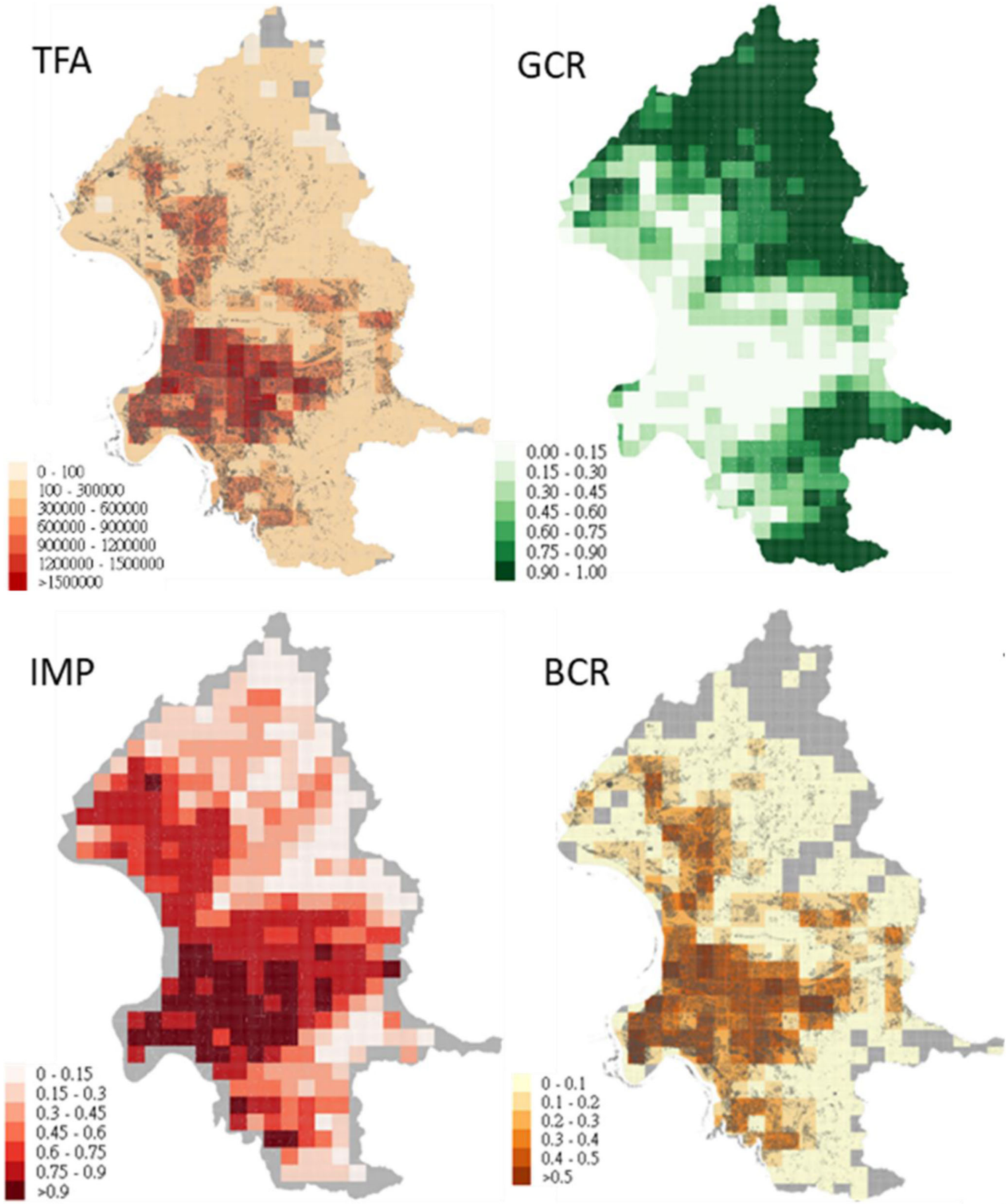

Fig. 1 Urban layers: total floor area (TFA), green area ratio (GCR), impermeable surface ratio (IMP), and building coverage ratio (BCR) in Taipei

(10:00–16:00) in Taipei (Fig. 3). The areas with higher thermal stress were located near districts with lower GCR values but with higher IMP, BCR, and TFA values. Considering the intense anthropogenic heat and poor ventilation for removing heat stored in the area, the central area of Taipei City is generally considered to be a city with high thermal load and UHI intensity.

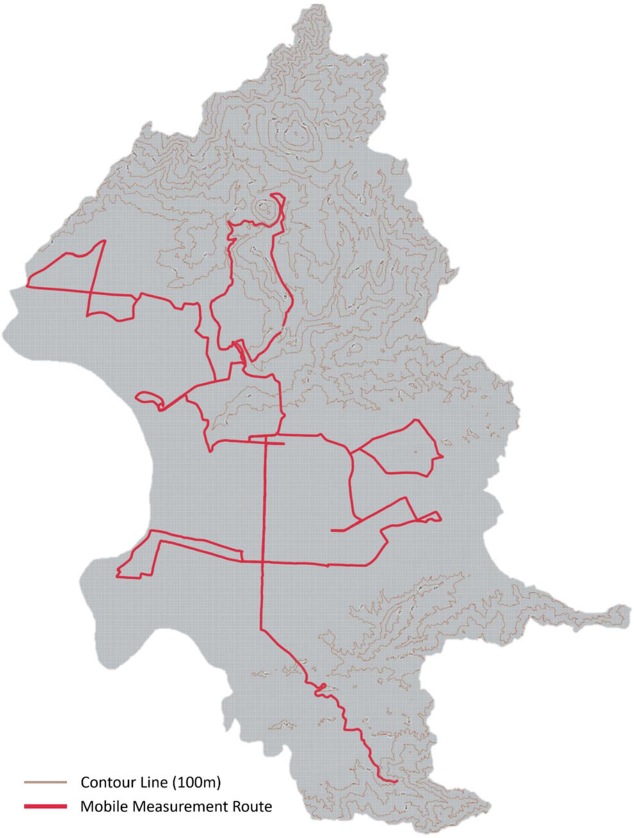

Fig. 2 Contour line and mobile measurement route in Taipei

3.2 Local climate zone distribution map

The results reveal that the areas that are mostly built-up in Taipei City are LCZ 2 (compact mid-rise), LCZ 5 (open mid-rise), and LCZ 9 (sparsely built). Moreover, LCZ 101 (dense trees), LCZ 102 (scattered trees), and LCZ 107 (water) dominate most of the non-built-up areas (Fig. 4). Generally, Taipei City is compactly developed in basin areas. The distribution map of LCZ reflects not only these geographical characteristics but also urban morphology in central areas where urban development information is not documented.

3.3 Relationship between air temperature and local climate zone

To understand the relationship between thermal distribution and land morphology, this study superimposes the UCmap onto the LCZ map (Fig. 5). In the built areas, LCZ 1, LCZ 2, and LCZ 3, which contain compact buildings (and, therefore, higher BCR and IMP values and lower GCR values), demonstrate higher Ta values than do other areas such as LCZ 4, LCZ 5, LCZ 6, LCZ 8, and LCZ 9, which have more vegetation or a smaller impermeable surface area.

Regarding the thermal characteristics of LCZ 101 and LCZ 102—which represents forests and parks, respectively, in the study area—the thermal stress is reduced, as there are large areas of vegetation and reduces anthropogenic heat. LCZ 107, which represents water (including rivers and lakes), has

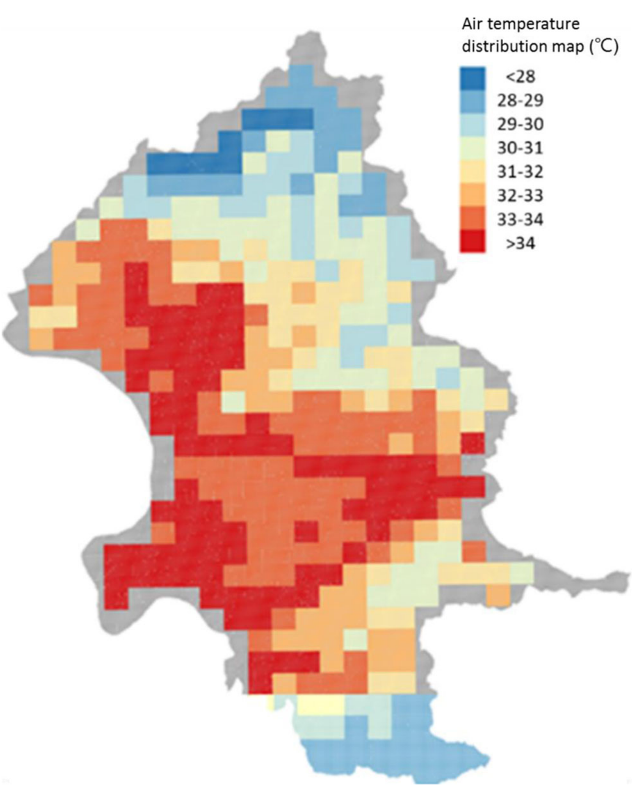

Fig. 3 Air temperature distribution map of Taipei

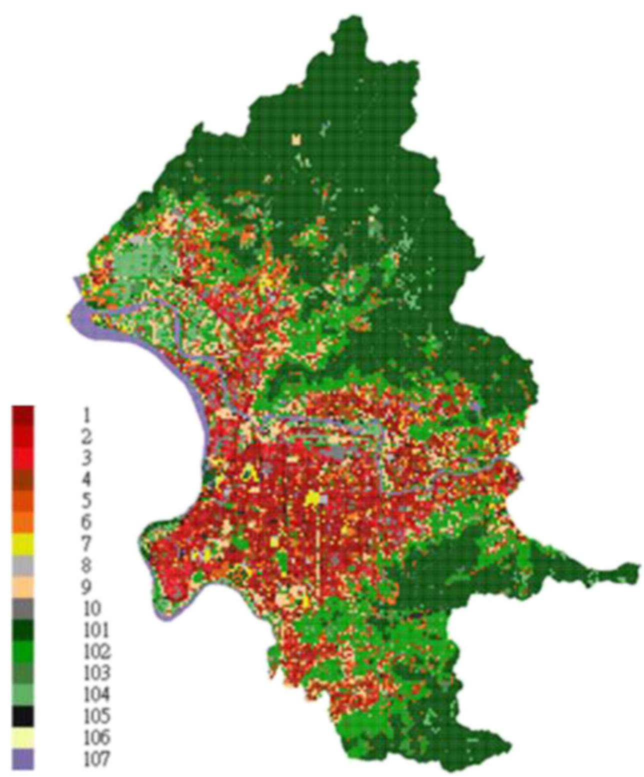

Fig. 4 Local climate zone map of Taipei

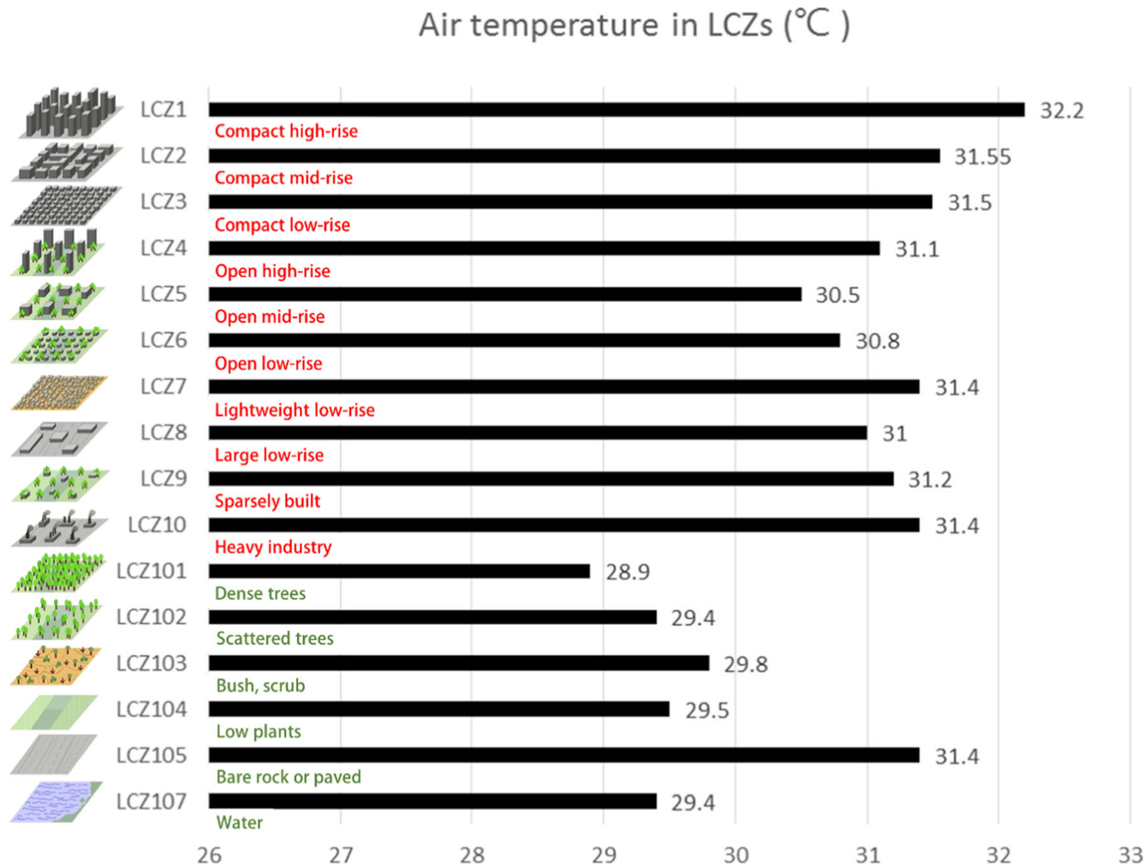

Fig. 5 Air temperature distribution of various LCZs in August 2016

reduced thermal stress: The surface in the area have greater heat-absorbing capacity, and its open surfaces improve ventilation, which carries away heat. These results are consistent with previous findings and suggest that water and green spaces impose cooling effect.

4 Discussion

The UCmap has been used widely used to assess microclimatic conditions in New Taipei City, Taichung City, Tainan City, and Kaohsiung City, as well as other cities around the world (Lin et al. 2014, 2017; Chen et al. 2016a, b).

In New Taipei City, airborne light detection and ranging and thermal images were used to determine the mean radiant temperature by analyzing land surface temperature and the shade of buildings. In Taichung City, a mobile measurement was taken to obtain the physiological equivalent temperature (PET). The urban development parameters in each district included land use, land cover, and building information were used to examine the effects of a thermal environment. Map for thermal risk and potential can be created to improve understanding of thermal conditions in the city. In Tainan City, the frontal area index, which estimates wind conditions by calculating the wind pass possibility value was added to a UCmap to evaluate the urban microclimate. In Kaohsiung City, an estimation model for the PET was obtained from research to detail the climatic characteristics of the city.

This study combines a LCZ map with a UCmap for examining the relationship between thermal condition and urban morphology. The LCZ classification scheme enables the interpretation of land development patterns and intensity from satellite images. As satellite images are increasingly publicly accessible, this method can be applied to different cities. This study argues that the LCZ and UCmap combination can be used to estimate thermal conditions and to improve the effectiveness of thermal predictions in the future. Therefore, decision-makers might adopt this approach to identify hot spots and to develop evidence-based mitigation strategies (Chen et al. 2017).

5 Conclusions

In this study, the UCmap and the LCZ were used to determine the relationship between microclimatic information in various LCZs and to elucidate the effects of complex urban structure and morphology on local climates. The results of this study can be applied to improve thermal comfort in urban areas.

In summary, a positive correlation was noted between Ta distribution and urban development. Higher building density, such as in LCZ 1, LCZ 2, and LCZ 3, is associated with higher temperatures. Urban planners who have inadequate meteorological knowledge can adopt this approach to comprehend urban thermal conditions in a given area; and to adjust the built environment structure from a certain LCZ type to another LCZ type for improving thermal comfort. The results suggest that LCZ 4, LCZ 5, LCZ 6, LCZ 9, LCZ 101, and LCZ 107 should be considered for future urban developments in Taipei City to mitigate local thermal stress.

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