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Evaluation on the outdoor thermal climate using an integrated urban canopy model and geographic information: a case study in Shenzhen

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1. Introduction

With the rapid urbanization of cities and the rise of climate change awareness, various methods and tools have been discussed to evaluate the thermal climate in different urban areas. Current studies usually adopted Computational Fluid Dynamics (CFD) simulation methods (Bustamante et al. 2014; Rodrigues et al. 2013) and field measurements (Brandsma and Wolters, 2012) to conduct the analysis of the urban local thermal climates. However, diversified underlying surface types and different building spatial patterns in urban space usually have more complicated urban local thermal environments (Leconte et al. 2015). The CFD simulation method could not well simulate the dynamic and complicated processes of complex construction areas (Murakami et al. 1990). Additionally, field measurements usually adopt long-term examinations based on meteorological observations and mobile surveys (Charabi and Bakhit, 2011; Acero et al. 2013), the results of which are usually discontinuous and limited to manpower and material resources. Therefore, an efficient dynamic prediction tool for examining thermal climatic distributions in a local urban district appears necessary.

In recent years, a single- or multi-layer urban canopy model was discussed and applied, which could calculate the meteorological parameters in a certain urban area by considering the heat and mass transfer calculations between the buildings, land, vegetation and atmosphere (Kondo et al. 2001; Masson 2000; Thank et al. 2000). However, most of the calculation results obtained for urban canopy models were premised on homogeneous underlying surface types and a single building function type. The existing urban canopy models cannot handle the complex construction spatial forms with multiple functions very well. Therefore, by integrating the advantages and limitations of the current urban canopy models, an improved multipurpose regional thermal climate prediction model (UDC) consisting of multiple coupled modules was proposed (Zhu et al. 2006; Mu et al. 2013). The UDC covered the urban atmosphere thermodynamic and dynamic characteristics and the effects on thermal climate caused by the thermal physical properties of various urban underlying surfaces. Above all, it could address the complex urban areas coexisting with multi-functional buildings and different underlying surface types.

This paper adopted the complex urban district of the International Low Carbon City (ILCC) in Shenzhen as the study area and conducted long-term dynamic simulations of the outdoor meteorological parameters of the whole ILCC by combining the improved urban canopy model UDC and the Geographic Information System (GIS). The distributions of each meteorological parameter in different local urban areas could be expressed, which would provide the intuitive visualization for local urban climate.

2. Method

2.1 Study area

This study adopted the International Low Carbon City (ILCC) of Shenzhen in the Pearl River Delta region in South China as the study area due to its wide coverage of diversified underlying surface types and building types. The ILCC has an area of 53.42 km^2, and the whole region is principally composed of green space such as trees and grass, water space, bare land, asphalt pavements and varied building types for industrial, residential and business uses. It has been divided into hundreds of region blocks by planners according to different architectural types and underlying surface compositions, as shown in Fig. 1.

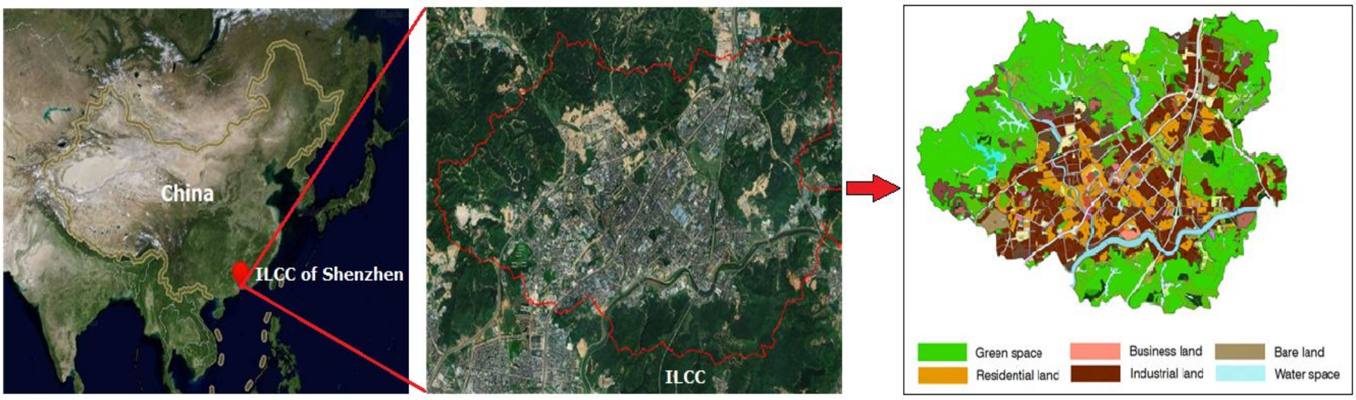

Fig. 1 Location and region block zoning map of ILCC

2.2 Calculation Model

The multipurpose regional thermal climate prediction model (UDC) consists mainly of five calculation modules, which are illustrated as follows.

The local climate calculation module: The basic equations for this module are primarily based on the urban canopy theory of Kondo but with modifications (Liu et al. 2006). The meteorological parameters only consider the vertical direction variations for the air between buildings and the atmosphere. Additionally, the construction configuration of the study area assumes that all of the buildings are square with equal distance between each other.

Building heat and moisture load calculation module: This module considers various building function types, covering residential districts, offices, commercial centers, hotels, stadiums, entertainment centers, schools and hospitals. For each building function type, the relative parameters of building envelopes, air conditioning systems and indoor loads were well considered by referring to the design standard for energy efficiency of different building types in Shenzhen. The parameter settings of industrial buildings, as an example, are described in Table 1.

Table 1. Parameter settings of industrial buildings.

Parameters		Values
Heat transfer efficient of building envelope/(W/(m2.K))	Exterior wall	1.5
	Roof	0.9
	Exterior window	3.0
Window-to-wall ratio	East, West, South, North	0.4
Air conditioning system	Indoor temperature/(°C)	28
	Indoor relative humidity/(%)	60
	Coefficient of performance	4.5
Indoor load	Occupancy density /(person/m^2)	0.02
	Equipment load/(W/m^2)	30
	Lighting load /(W/m^2)	5
	Air change rate /(1/h)	6

Thermal process calculation module between the underlying surface and the atmosphere: This module includes all types of underlying surface types that exchange heat and moisture with the atmosphere in actual urban areas as well as impervious artificial surfaces (e.g., asphalt road, concrete), bare land, green spaces (grass and trees), and water surfaces (Zhu et al. 2011).

The solar radiation calculation module: This module adopts the ray tracing method and assumes that the attenuation effect on solar radiation caused by trees is simply a function of the distance of the light waves passing through the tree crowns.

Thermal comfort calculation module: This module calculates the standard effective temperature (SET*) (Gagge et al. 1986), which has been widely adopted for assessing outdoor thermal comfort as an important index (Spagnolo and de Dear, 2003). SET* is acquired through the heat transfer process between human bodies and the ambient air based on a human physiological reaction model.

Additionally, the related validations for UDC within the structured residential districts and the complex commercial-residence building areas were both illustrated in previous studies (Zhu et al. 2007; Rao et al. 2013). The whole structural diagram of UDC is displayed in Fig. 2. Therefore, with the hourly meteorological data of local weather station and the input parameters of certain localized urban area, the simulating calculations could be conducted.

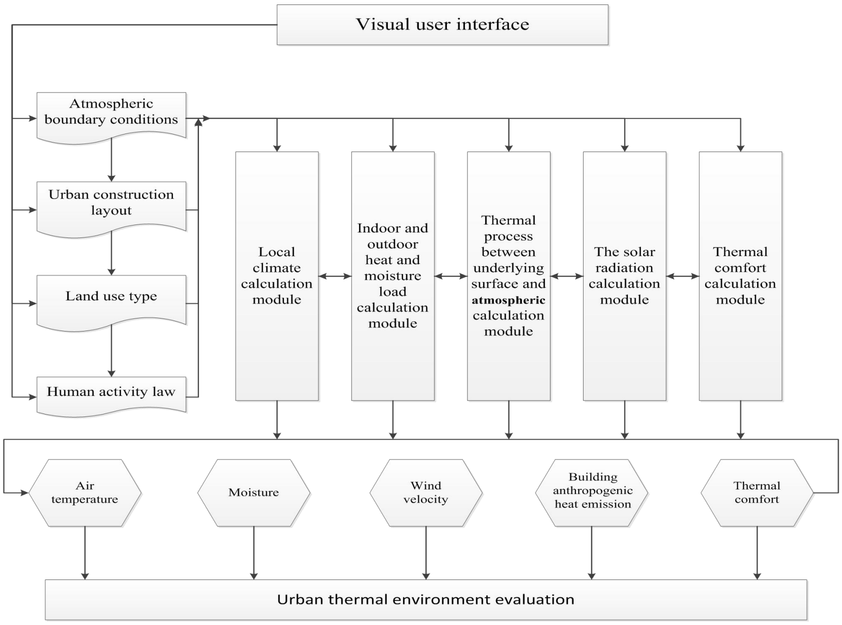

Fig.2 Structure diagram of UDC model

2.3 Calculation conditions

The hottest summertime was the main study objects. Therefore, the official meteorological data of July in the year 2013 was considered as the basic calculation meteorological conditions. Besides, as the land use types and the construction spatial patterns of each urban block were different from each other, different building function types, various building floor area ratios and multiple underlying surface types of each urban block were expressed by some corresponding parameters of buildings and underlying surfaces. With the spatial positions of these blocks and the basic geographic information database of Shenzhen, the relative parameters of construction space and underlying surfaces within each block were calculated by GIS. Therefore, the input conditions and parameters of each block were prepared for UDC and the hourly thermal climatic parameters of each block could be calculated. Further with the visualization by GIS, the urban climatic distribution maps (Ren et al. 2011) of different meteorological parameters could be then obtained.

3. Results and Discussion

This paper mainly focused on the spatial distributions of different meteorological parameters, including air temperature (T_a), relative humidity (RH), wind velocity (V), standard effective temperature (SET*). As the calculation interval lasted for a month, the average values of these parameters during the simulating interval were mainly considered and discussed. The spatial distribution maps of them within different urban blocks of ILCC were revealed in Fig.3.

As described in Fig. 3, the spatial distribution map of T_a during the daytime reveals that urban blocks in the middle of the whole ILCC region appear higher temperature than the peripheral urban blocks obviously. The reason may be that compared to the middle urban blocks with building clusters, the peripheral urban blocks are mainly covered with trees which significantly blocked the solar radiation from reaching the inner space and the transpiration of leaves would also contribute to lower the temperature. Besides, through the calculation results of all the region blocks, it can be concluded that the average temperature of the middle urban blocks is 29.94℃ while that of the peripheral urban blocks is 28.31℃. The results significantly emphasized a local urban heat island effect of about 1.6 ℃ existing in the ILCC region.

The moisture content distribution map shows that the peripheral urban blocks appear much higher moisture content values compared to the middle urban blocks from an overall perspective. Through calculation, it revealed that the middle urban blocks had an average moisture content value of 0.018kg/kg while the peripheral urban blocks got an average value of 0.021kg/kg. This phenomenon illustrates that the transpiration of plenty of trees of the peripheral areas had produced a large amount of moisture and increased the moisture content.

The wind velocity distribution map shows that the wind velocity of most blocks shows a medium value varying from 0.25m/s to 0.35m/s while the area with waterbody presents a very high wind velocity value. Several blocks of the middle urban areas show a very low wind velocity value. The reason is that the middle urban blocks with the lowest wind velocity show a quite high plot ratio with intensive buildings, which greatly blocked the wind from blowing and caused the severe wind attenuation. Similarly, since the peripheral urban blocks are mainly covered with trees which would also weaken the wind velocity, thus forming the medium value in most of the whole blocks. The waterbody presented the highest wind velocity on account of lacking any effective shield against the wind.

The SET* was regarded as an index to evaluate the overall thermal comfort of the corresponding urban block. Its distribution map displays that most middle urban blocks showed the lower SET* values and the values of peripheral urban blocks appeared a medium level. However, the waterbody and several urban blocks in the middle area displayed the highest SET* values. Based on the land use data, the urban blocks with lower SET* usually have a higher building floor-area ratio which could greatly blocked the solar radiation. The urban blocks with higher SET* values are filled with bare land space which usually absolutely exposed to the solar radiation. Since SET* is affected by various thermal climatic parameters such as the air temperature, humidity content, the wind velocity and solar radiation, it was the result from the joint effects. The results also emphasized that the outdoor thermal comfort in summer is primarily affected by solar radiation, which is actually influenced by different underlying surface conditions. Therefore, appropriate urban design by comprehensively considering the underlying surface compositions seems important to realize the thermal comfortable urban climate.

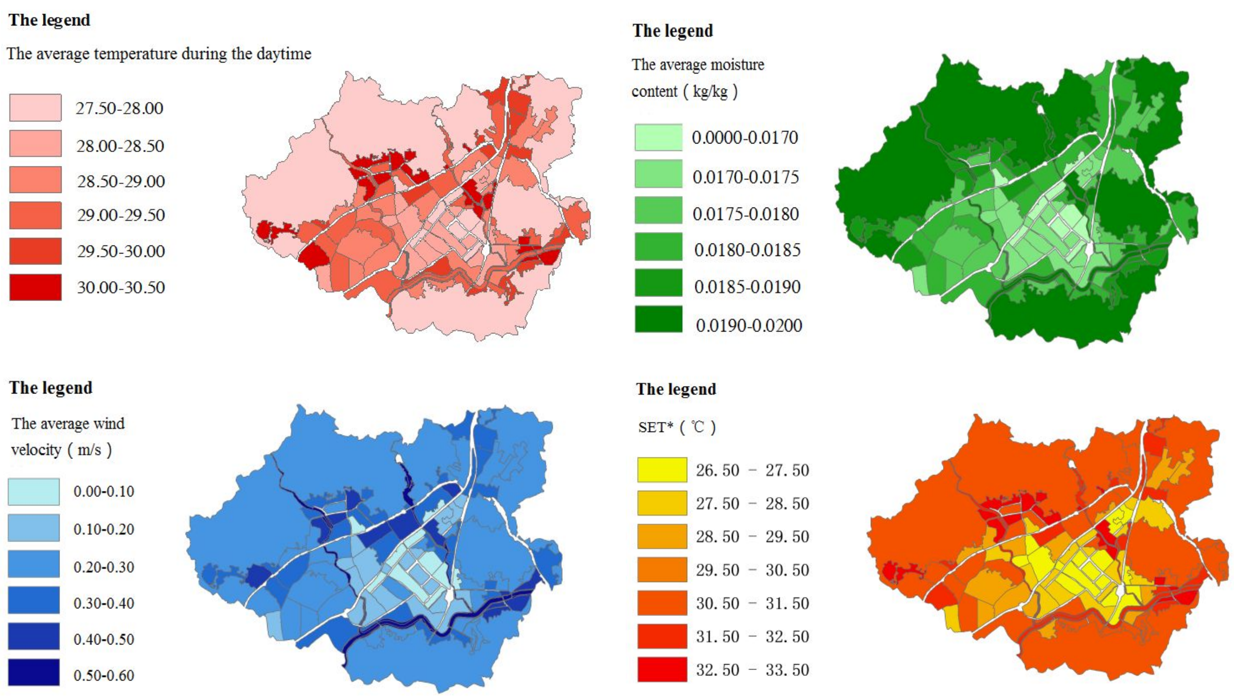

*Fig.3 Spatial distribution maps of T_a, RH, V, SET**

4. Conclusions

This paper conducted a long-term dynamic simulation of the summertime thermal environment in the ILCC of Shenzhen by a UDC model. The spatial distribution maps of different meteorological parameters, including air temperature (T_a), relative humidity (*RH*), wind velocity (*V*), standard effective temperature (SET*) were obtained by combining GIS. Results show that the parameters in different urban blocks varied a lot due to their different underlying surface compositions. The distributions of comprehensive thermal comfort index SET* emphasized that a climatic conscious urban design is necessary.

Acknowledgment

The authors would like to thank the open project of the State Key Laboratory of Urban Resource and Environment (Grant No. 2010TS04), the Shenzhen Science & Technology Development Funding-Fundamental Research Plan (Grant No. JCYJ20120615145601342 and JCYJ20130325151523015) and the Key Laboratory of Eco Planning & Green Building, Ministry of Education (Tsinghua University, 2013U-6) for financially supporting this research.

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