Dynamic Spatial-temporal Evaluations of Urban Heat Islands and Thermal Comfort of a Complex Urban District Using an Urban Canopy Model

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Abstract
This study conducted hourly dynamic simulations of the thermal climate and thermal comfort of 120 blocks within the complex district of the International Low Carbon City (ILCC) by applying an urban energy balance model (UDC), during the summertime in Shenzhen. Two parameters, including the local urban heat island (LUHI) and SET*, were adopted as evaluation indices, and the temporal-spatial distributions of these parameters were discussed. The results show that the northeast blocks of the ILCC always presented higher values of LUHI and SET* compared with the lower values of the middle blocks. The LUHI values varied between different blocks at the same time, ranging between -4°C and 4°C, whereas the SET* values varied from 27.5°C to 33.5°C. The large differences in the LUHI and SET* values between these blocks may be caused by their different urban spatial patterns and the varied underlying surface compositions. Additionally, the average diurnal variation of LUHI showed more fluctuations compared with the continuous conic variation manner of SET*. The average maximum values of LUHI and SET* both occurred in the afternoon, whereas the average minimum values occurred in the early morning.

Keywords: urban energy balance model; spatial-temporal simulation; local urban heat island; thermal comfort

1. Introduction
With the expansion of cities and the rise of climate change awareness, various methods and tools have been developed to analyze the thermal climate and thermal comfort in different urban areas. Compared to monitoring techniques, since its convenience and effectiveness in predicting and evaluating the thermal climatic conditions, urban meteorological modeling has become a significant supplementary approach in different applications, such as urban design, air quality forecasting, city energy and transportation management and so on (Liu et al. 2006; Oleson et al. 2008; Lemonsu et al. 2004; Snelder and Calvert, 2016).

It should be noted that currently, the common urban climatic numerical simulation methods all have their own limitations. The Computational Fluid Dynamics (CFD) technology (Murakami et al. 1990; Takemi and Rotunno, 2003) is mainly for steady-state simulations of the microscale areas in the urban meteorological field and not suitable for accurately simulating the long-term dynamic local climatic variations of complex construction areas owing to the limited computing ability and modeling complexity. Additionally, the atmospheric mesoscale models (Jimenez and Dudhia, 2012; Dudhia 2014) are mainly used with grid sizes of tens of kilometers or in cloud-resolving scales for regional climate applications. The lower spatial-resolution of these models cannot clearly reflect the effects of underlying surface morphology on the local climates.

Compared to the steady-state models and mesoscale models mentioned before, the urban energy balance (UEB) models are widely used to accurately predict fluxes at the local scale (10²–10⁴m) (Oke 1982; 1988). The UEB models simplified the urban areas into continuous similar building groups without limiting to complex urban layouts and then conducted the heat and mass transfer calculations between the buildings, land,
vegetation and atmosphere (Grimmond et al. 2010). Since the UEB model originally served as a local-scale urban meteorological parameterization scheme, it is well suited for long-time local-scale dynamic climatic simulations. In recent years, some single- or multi-layer urban energy balance models have been developed to incorporate urban features for different applications in climate modeling and weather prediction, such as the Urban Canopy Model and Town Energy Balance (Grimmond and Oke, 2002; Kondo et al. 2001; Masson 2000; Kanda et al. 2005). However, most current UEB models are premised on homogeneous underlying surface types and a single building function type. Apparently, this causes great discrepancy in the simulation results of the actual complex construction spatial patterns for different functional uses.

Considering the advantages and limitations of the application of conventional UEB models, this paper introduced a simulation technique by combining an improved urban energy balance model with the Geographic Information System (GIS). With this developed technique, the long-term dynamic simulations of the thermal climatic conditions in the International Low Carbon City of Shenzhen were conducted based on the block divisions in urban planning. Additionally, the temporal-spatial distributions of the local climatic parameters were then expressed for detailed analysis.

2. Study Area
The International Low Carbon City (ILCC) of Shenzhen is located in the Pearl River Delta region in South China. Fig.1. shows the location and the general present underlying surface conditions of ILCC. It has an area of 53.42 km$^2$ and the current land use types are mainly industrial and residential buildings. As a demonstration zone for realizing the climate friendly urban area, the ILCC needs reliable evaluations on its thermal climate and thermal comfort for future appropriate urban planning.

3. Methodology
3.1 Calculation Model
This study adopted a multipurpose regional thermal climate prediction model (UDC) as the calculation model, which consists of multiple coupled modules (Hagishima et al. 2001; Zhu et al. 2007; Mu et al. 2013). The UDC was derived from the fundamentals of the urban canopy model and was further improved by covering the dynamic thermodynamic characteristics of urban atmosphere and the effects of various urban underlying surfaces with multi-functional building types on urban thermal climate. The five sub-modules contained in UDC are illustrated as follows.

- The local climate calculation sub-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 variables 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 sub-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.

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

- Thermal process calculation sub-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 sub-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 sub-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 (Spangholo 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.

The main basic theoretical equations applied in sub-modules of UDC were briefly listed in Table 2. The related validations for UDC within the structured residential districts and the complex building areas were both illustrated in previous studies (Zhu et al. 2006; Rao et al. 2013).

### 3.2 Preliminary Calculation Conditions
To quantitatively describe the ILCC, the entire area was divided into 120 small blocks, according to their different land use types for various functions, as shown in Fig.2. The area surrounded by the blue line in Fig.2 expresses the main urban area, whereas the other seven blocks, which are mainly filled with green or water space, represent the suburban area of the ILCC. The land use types and the construction spatial patterns of each block were different from each other and were expressed by different building function types, various building floor area ratios and multiple underlying surface types. 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. For example, block No. 28 and its

| Table 2. The Main Basic Theoretical Equations in UDC |
|------------------------------------------------------|
| **Consideration aspects** | **Theoretical equations** | **Main parameter interpretations** |
| **Momentum** | \( \frac{\partial U(z,t)}{\partial t} = \frac{1}{\rho(z,t)} \left( m \frac{\partial (u'w')}{\partial z} \right) + \alpha c U[k]\) | \( U(z,t) \) is the wind velocity, \( m \) is the density, \( \alpha \) is the e analogy factor, \( c \) is the heat capacity. |
| **Heat** | \( pc_V \frac{\partial \Theta(z,t)}{\partial t} = pc_V \frac{1}{\partial m \frac{\partial (\Theta w')}{\partial z}} + G \) | \( pc \) is the specific heat, \( \Theta \) is the temperature, \( G \) is the solar radiation. |
| **Moisture** | \( \rho V \frac{\partial \Theta(z,t)}{\partial t} = \rho V \frac{1}{\partial m \frac{\partial (\Theta w')}{\partial z}} + S \) | \( \rho \) is the density, \( V \) is the velocity, \( S \) is the moisture sink. |
| **Eddy diffusion** | \( \langle u'w' \rangle = K_n \frac{\partial u}{\partial z} - \langle \theta'w' \rangle = K_s \frac{\partial \Theta}{\partial z} - \) | \( K_n \) is the turbulent diffusion coefficient. |
| **Building heat and moisture load** | \( R \frac{\partial U(z,t)}{\partial t} = \int \sum A_i \theta_i \) | \( R \) is the heat and moisture load, \( A_i \) is the heat and moisture transfer coefficient. |
| **Heat exhaust of air conditioning system** | \( \hat{Q}_{a} = \left( 1 + \frac{1}{COP} \right) \) | \( \hat{Q}_{a} \) is the heat exhaust of air conditioning system. |
| **Heat balance equation of underlying surface** | \( R_{0j} = R_{s} - \epsilon_{j} \sigma T_{j}^{4} + \epsilon_{j} (F_{j} R_{s} \downarrow + \sum_{j} F_{j} \epsilon_{j} \sigma T_{j}^{4}) \) | \( R_{s} \) is the net radiation fluxes, \( \epsilon_{j} \) is the emissivity. |

- Sensible and latent heat flow:
  - Trees—\( H_s, E_{\phi} \)
  - Impermeable pavement—\( H_s, E_{\phi} \)
  - Bare land—\( H_s, E_{\phi} \)
  - Grass—\( H_s, E_{\phi} \)
  - Waterbody—\( H_s, E_{\phi} \)

### Definition of SET*
\( Q_{a} = \alpha'_{SET} \left( T_{a} - SET^{*} \right) + \alpha''_{SET} \left( P_{a} - 0.5P_{SET} \right) \)

\( Q_{a} \) is the skin total heat release, \( T_{a} \) is the skin temperature, \( P_{a} \) is the vapor partial pressure of skin surface, \( P_{SET} \) is the saturated water vapor pressure, \( k \) is the Pa.
corresponding parameters are shown in Table 3.

This study primarily focused on the summertime thermal climate of the ILCC by considering the hottest four weeks from July to August as the computing interval. The hourly meteorological data derived from the meteorological database dedicated for Chinese building thermal environmental analysis, which was developed by the cooperation of the Meteorological Reference Room of the Chinese Meteorological Information Center and the Construction Engineering department of Tsinghua University. Additionally, the solar radiation data covered the effect caused by the presence of clouds. Therefore, the weakening effects of clouds on solar radiation were not considered in the calculations. Additionally, topographic effects were not considered in this study.

By importing the meteorological data and the urban spatial parameters for all 120 blocks, as calculated by GIS, into the visual user interface of the UDC, dynamic calculations of each block were performed in turn. Then, hourly data of air temperature, moisture, wind velocity, anthropogenic heat emissions from buildings and the thermal comfort at a height of 1.5 m from the ground could be obtained for each block. All the hourly results for all 120 blocks were then imported back into the GIS according to their spatial positions to realize the visualizations of the temporal-spatial distributions of the thermal climate and thermal comfort of the ILCC. A flow diagram of this technique is displayed in Fig.3.

### 3.3 Evaluation Indices

As an important evaluation index of the urban thermal climate, the Urban Heat Island (UHI) has been widely used (Sofer and Potchter, 2006) and is usually defined as the difference between temperatures measured in the urban space to those in the non-urban space surrounding it (Oke, 1987). This paper proposed the definition of local urban heat island (LUHI) of each block in the ILCC as the evaluation index, as shown in Equation (1):

\[
LUHI_i = T_i - \frac{1}{7} \sum_{j=1}^{7} T_{sj} 
\]

Where the \( LUHI_i \) represents the LUHI value of the \( i \)-th block, \((1 \leq i \leq 120)\); \( T_i \) displays the air temperature of the \( i \)-th block; and \( T_{sj} \) represents the air temperature of \( j \)-th suburban block. Then, the average air temperature of the seven suburban blocks were considered the suburban benchmark temperature. With the hourly air temperature of each block, the hourly LUHI distributions of the ILCC could be obtained.

Then, the thermal comfort evaluation index \( SET^* \) of each block could be calculated hourly by using the thermal comfort calculation module of the UDC. When calculating the \( SET^* \), this paper assumed that people were standing leisurely in an outdoor urban space during the summertime. Therefore, the human metabolic rate was set at 72 W/m\(^2\), the human mechanical work was set at 0 W/m\(^2\) and the clothing thermal resistance was set at 0.3 clo. The hourly distributions of \( SET^* \) were thus obtained to conduct spatial-temporal evaluations on the thermal comfort of the ILCC.

### 4. Results and Discussion

#### 4.1 The Spatial Distributions of LUHI at Different Times

Having averaged the LUHI values at each hour during the whole calculation period of each block within the ILCC, the spatial distributions of LUHI at different times of the day were expressed. This study primarily discusses the LUHI spatial distributions at the representative times of 5:00, 13:00 and 21:00 to conduct the analysis, as depicted in Fig.4. Table 3. Urban Spatial Parameters of Block No. 28

| Urban spatial parameters          | Values  |
|----------------------------------|---------|
| Total area of the block (m\(^2\)) | 221237  |
| Building floor-area ratio        | 1.89    |
| Average height of buildings (m)  | 28      |
| Area ratios of different         |         |
| underlying surface types in      |         |
| the whole block                  |         |
| Asphalt road                     | 0.3     |
| Bare land                        | 0       |
| Grass                             | 0.136   |
| Trees                             | 0.337   |
| Water                             | 0       |
| Industrial                        | 0.6     |
| Official                          | 0.02    |
| Area ratios of different building function types in the total building area | 0.18    |
| Residential                       | 0.2     |
| Commercial                       |         |

Fig.2. The Main Land Use Types of 120 Blocks within the ILCC (The Area surrounded by the Blue Line is the Main Urban Area and Block No. 28 was Used as an Example)
Taken together, all three distributions demonstrate that the northeast part of the main urban area revealed higher LUHI values, whereas the middle part expressed lower LUHI values. Different blocks’ LUHI values of the same time had obvious differences between each other. The maximum LUHI value was 4°C, whereas the minimum LUHI value was as low as -4°C. This phenomenon illustrated the great effect on the local thermal climate caused by urban spatial forms and the underlying surface properties of different blocks. The blocks with lower LUHI values usually had higher building floor area ratios, which greatly prevented the sun radiation from reaching the inner space and thus lowered the air temperature of such blocks. Additionally, the underlying surfaces of the blocks with lower LUHI values were usually filled with water space or tall trees. The transpiration of the tall trees and the evaporation of the water space could decrease the air temperature of the surroundings. Additionally, the tall trees blocked incoming solar radiation and further cooled the ambient air temperature. In contrast, the blocks with low-growing vegetation and sparse buildings with lower building area ratios showed higher LUHI values due to the lack of appropriate shelter from sunlight. From the temporal perspective, the LUHI values at 5:00 in the early morning presented lower values overall, whereas the LUHI values of most blocks increased considerably by 13:00 in the afternoon. At 21:00 in the evening, the LUHI values of the majority of the blocks decreased again to a low level.

4.2 Diurnal Variation of the Overall Average LUHI

To reveal the LUHI diurnal variations, the overall average values for all of the blocks at each hour
throughout the calculation period were obtained, as shown in Fig.5. The diurnal variation range of the overall average LUHI values was between -0.4°C and 0.6°C, the gap of which was less than 1°C. However, Fig.4. shows that the LUHI values of different blocks at the same time changed from -4°C to 4°C, with the gap reaching 8°C. This phenomenon was the result of the comprehensive effects of all the blocks with both the higher LUHI values and the lower LUHI values on the overall average values. In addition, the overall average LUHI had a minimum value of -0.37°C at 5:00 in the early morning and reached a maximum value of 0.57°C at 14:00 in the afternoon. The overall average LUHI values were below 0°C before 8:00 in the morning, which showed that the average air temperature of the main urban area was even lower than that of the suburban area. This phenomenon may be due to the lower artificial heat emissions and the small amount of sunlight absorption during the period from midnight to 8:00. Additionally, the fluctuations in the daytime were much more severe than those that occurred at night after 18:00.

4.3 The Spatial Distribution of SET* at Different Times

The average SET* spatial distributions at the typical times of 5:00, 13:00 and 21:00 during the calculation period were considered and are described in Fig.6. In these three maps, the SET* difference between the highest and lowest values within the ILCC reached 10°C or more for the same time. The northeast part always showed higher SET* values compared with other parts, whereas the middle part showed lower SET* values due to the difference in the urban spatial patterns and the underlying surfaces of different blocks. This phenomenon was similar to that of the LUHI distributions. The blocks with higher building floor area ratios and tall trees could effectively block the solar radiation, and the substantial water space within the blocks could lower the air temperature by evaporation, which contributed to lowering the SET* values and thus increased the human thermal comfort. In particular, the SET* values of the surrounding suburban blocks with plenty of tall trees and water were not lower than those of some blocks in the middle part. This phenomenon was slightly different from that of the LUHI distributions. The reason may be that the SET* was affected by a variety of parameters, such as air temperature, relative humidity, wind velocity, and solar radiation. Although the numerous tall trees of the suburban blocks greatly prevented solar radiation from penetrating the inner space, they also lowered the wind velocity. Additionally, the large area of trees and water increased the moisture in the air. Thus, the lower wind velocity and increase in moisture greatly increased the SET* values of these suburban blocks. To summarize, the diversified SET* distributions were a consequence of comprehensive interactions among multiple factors.

Additionally, the SET* values of most blocks at 5:00 in the early morning were lower. However, the spatial distribution map at 13:00 in the afternoon revealed that the SET* values of almost all of the blocks in the ILCC were over 30°C and even reached 34.5°C or more. Then, at 21:00 in the evening, the SET* values...
of these blocks decreased to approximately 30°C. The appearances of these three maps illustrate an obvious difference in the SET* distributions at different times.

4.4 Diurnal Variation of the Overall Average SET*

The overall average SET* diurnal variations during the calculation period are displayed in Fig.7. As a whole, the overall average SET* values presented drastic changes in a conic variation manner. The overall variation range was between 27.5 and 33.06°C. The maximum overall average SET* value occurred at 16:00 in the afternoon and the minimum value occurred at 5:00 in the early morning. The times when the extreme average values of SET* occurred were similar to those of the LUHI. Therefore, both the average values of the LUHI and thermal comfort of the ILCC achieved optimal levels in the early morning and the worst level in the afternoon. However, the overall average SET* diurnal variation process was relatively smoother than the repetitive dramatic fluctuations that occurred during the overall average LUHI diurnal variation process. The main reason may be that the air temperatures of both the main area and the suburban area were always changing; therefore, the LUHI values calculated by considering the air temperature difference cannot ensure continuity. The calculations of SET* are derived from the continuously changed meteorological variables and thus resulted in a relatively smooth variation line.

5. Conclusions

In this paper, we conducted hourly dynamic simulations of the thermal climate and thermal comfort of blocks within the ILCC by applying a combination of the urban canopy model UDC and GIS. The temporal-spatial distributions of the two representative parameters of LUHI and SET* are mainly discussed. The results revealed that the northeast part of the ILCC presented higher values of LUHI and SET*, whereas the middle part showed lower values. The LUHI values of these blocks at the same time varied between -4°C and 4°C, whereas the SET* values of different blocks at the same time varied from 20.5°C to 37.5°C. The great difference between these blocks may be due to their different urban spatial patterns and varied underlying surface compositions. In particular, the suburban blocks with plenty of tall trees and water space did not show the lowest SET* values due to the comprehensive effect of multiple parameters. Additionally, the overall average LUHI diurnal variation presented continuous fluctuations, whereas SET* showed a continuous conic variation manner because of their different calculating considerations. Additionally, both the overall average variations of LUHI and SET* showed maximum values occurring in the afternoon and minimum values occurring at 5:00 in the early morning.

It should be noted that like a conventional UEB model, the UDC model used in this study is a one-dimensional calculation model for conducting dynamic long-term simulations effectively. Therefore, it was applied in the scale of a single block in this study. Within each block, it is assumed that under the conditions of relatively lower wind velocity, the vertical variations of meteorological variables are much larger than the horizontal variations, therefore the local climatic characteristics are mainly influenced by the local underlying surface patterns and anthropogenic heat within the mosaic land usage. The spatial climatic distributions were expressed including the calculation results of all the blocks. However, the horizontal thermal interaction among blocks caused by advection effects is also an important factor which can influence the thermal climate in a complicated urban area, especially under the conditions of high wind velocity and underlying surface with large area monotonicity, such as an urban waterbody. This point should be further considered and discussed in future simulation modeling.

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