THE DYNAMIC PREDICTION ON OUTDOOR THERMAL CLIMATE IN A COMPLICATE URBAN COMPLEX

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ABSTRACT

The urban complex with multi-function and multi-form has become an important architectural mode in the modern urban development process. By combining the building features of urban complex and the types of its air conditioning system, an urban complex thermal climate prediction model was developed and applied in a southern planning project as an actual subject to simulate and analyze the outdoor thermal climate in urban complex. At last, this paper proposed the effective measure to improve the thermal climate in urban complex by changing the related impact parameter of the urban thermal climate. The result shows that the outdoor temperature in this regional is apparently reduced by increasing the urban greening rate.

INTRODUCTION

In recent years, the rapid urbanization process accompanied by an increase in anthropogenic heat released, changes in surface coverage, and a reduction in green space, has significantly changed the regional climate in the urban area and caused various environmental problems such as heat island and so on.

Considerable studies have been carried out on outdoor thermal environment. Marialena et al. studied environmental and comfort conditions of open spaces in cities by questionnaire in 14 different case study sites and across 5 different countries in Europe (Marialena and Spyros, 2006). Lin et al. and Dimoudi and Nikolopoulou studied the effect of vegetation on urban microclimates using CFD analysis on a simple model of an urban block (Lin et al., 2008; Dimoudi and Nikolopoulou, 2003). Mohamad and Stephen investigates how urban form can be designed to act as a passive thermal comfort system in Cairo using ENVI-met Numerical simulations in hot climate conditions (Mohamad and Stephen, 2009). These studies could only make a general analysis of outdoor thermal in an urban block. However, there are few studies make a detailed analysis of heat and moisture emission from various sources (as green land, building and so on) and their impact on thermal and humid environment in the urban complex. The major reason is that the urban complex has multi-type buildings and complex energy-using form, and heat emission from air-conditioning equipment of difference types buildings can be sensible heat or latent heat or the both, therefore the outdoor environment in urban complex is considerably more complicated.

In recent years, the urban complex, a new building mode with many advantages such as: multi-function, compact structure and high efficient, has been developed rapidly and applied widely as a healthy and sustainable urban growth pattern to meet the increasingly diversified society living requirements (Dong, 2005). In China, both the major cities and some second-tier cities have already built many urban complexes (Dong and Lu, 2009; Shi and Pan, 2010).

Unlike other conventional building blocks, the urban complex contains three or more different types of buildings, and each part is interdependent and forms an organic whole system. Additionally, the floor area ratio of the urban complex is generally up to 3 to 5, which is higher than the common building. However, due to the large space volume, diverse architectural features, as well as the complex energy-using form and different forms of heat emission (e.g., the sensible and latent heat), the thermal and humid environment in urban complex is more complicated than the area with a single type of building (Ichinose et al., 1999), as a result of the above factors, the relevant research of outdoor thermal climate in complex urban is still very lacking up to date (Wang et al., 2007; Harada et al., 2005).

In this study, the main purpose is to develop a revised urban complex thermal climate prediction model by considering the heat emission from various sources, especially the heat emission from the different types of buildings in the urban complex basing on the developed model (Zhu et al., 2007). Then this model is applied to an actual urban complex project in the southern of China for the dynamic simulation and analysis the outdoor thermal climate during the whole calculation period. Furthermore, this study proposes the effective method to improve the outdoor thermal climate and to decrease the heat island intensity in urban complex, and ultimately provide a reference for the future urban complex planning and construction (Gong and Wu, 2005; Shashua and Hoffman, 2000).

THE MODEL OF THE THERMAL CLIMATE IN URBAN COMPLEX

This study add the heat and moisture emission model of the various types buildings into the developed urban thermal climate prediction model(Zhu et al., 2007) which basing on the one-dimensional coupled urban-building energy evaluation model AUSSSM (Hagishima et al., 2001). The rationality of this model has been verified by field measurements (Zhu et al., 2006). The model consists of several components, such as: the local climate module, the building thermal and moisture load calculation module, the solar radiation calculation module, the thermal comfort module and so on. All these modules are coupled with each other that dynamic calculation results of thermal climate condition and energy exchange in urban complex can be obtained.

The basic framework of this model is shown in Figure 1. Several typical kinds of buildings such as residential, office, commercial and financial centre, hotel, sports centres, entertainment centres, schools, hospitals and other common building types in urban complex are taken into account. By entering data as: the physical properties of the building envelope, the form of air conditioning system and its operating time, setup of indoor A/C temperature and humidity, ventilation rate, generation rate of indoor sensible heat and latent heat, this model can complete the dynamic simulation of air conditioning load and anthropogenic heat exhaust of building in urban complex that includes multiple types of buildings.

Calculation of heat emission from building

- Calculation of heat transfer through building exterior wall

The heat transfer through building walls is assumed to be unsteady one-dimension heat tranfer basing on the differential principle. The equation is：

$$\alpha_{c,i}\left(\theta_{w,i}-\theta_m\right)+k_m\sum_{k=1}^{N_m}F_{ik,m}\left(\theta_{w,i}-\theta_{w,k}\right)+\left(q_{x,i}\theta_{w,i}-\sum_{j=1}^{N}z_1\left(i,j\right)q_{y,ji}\theta_{w,j}-\sum_{l'=L+1}^{L'}z_2\left(i,l'\right)q_{y,j'i}\left(\theta_o+\frac{a_{j'}}{\alpha_o}I_{j'}\right)\right)=\left(\beta_i/A_i\right)S_m+U_{w,i} \quad (1)$$

Where $\alpha_{c,i}$ (W/m^2·K) is the convective heat transfer coefficient of wall i; $\theta_{w,i}$ (°C) is the temperature of wall i; θ_m (°C) is the air temperature of room m; $q_{x,i}$ is the heat absorption response of wall I; $q_{y,ji}$ is the thermal response of wall i and j that faced the same interior wall; $z_1(i,j)$, $z_2(i,l')$ are the determine function(valve is 1 when i=j or i=0,other is 0); θ_o (°C) is the outdoor air temperature; α_o (W/m^2·K) is the integrated heat transfer coefficient of the outdoor; $U_{w,i}$ (W/m^2) is the direct radiation except the solar radiation of unit area of wall i; S_m (W/m^2) is the mount of solar radiation enter the room m; β_i is the ratio of radiation absorption to the solar radiation; A_i (m^2)is the surface area of wall i.

- Calculation of heat transfer through building window

The calculation of heat transfer through the windows is assumed as a steady one-dimensional progress:

$$\alpha_{c,i}\left(\theta_{g,i}-\theta_m\right)+\sum_{k=1}^{N_m}F_{ik,m}\left(\theta_{g,i}-\theta_{g,k}\right)+K'\left(\theta_{g,i}-\sum_{j=1}^{N}z_1\left(i,j\right)\theta_{g,j}\sum_{l'=L+1}^{L'}z_2\left(i,j\right)\left(\theta_o+\frac{a_{j'}}{\alpha_o}I_{j'}\right)\right)=\left(\beta_i/A_i\right)\left(a_i/a_i'\right)S_m+U_{g,i} \quad (2)$$

Where K' (W/m^2·K) is the heat transfer coefficient of window; $\theta_{g,i}$ (°C) is the temperature of window i.

- Calculation of heat emission from building air-conditioning system

The heat and moisture emission from different types of buildings are as follows:

$$c_p\rho V_{m,j}\frac{d\theta^r_{m,j}}{dt}=\sum A_{m,i,j}\alpha(\theta^w_{m,i,j}-\theta^r_{m,j})+c_p\dot{m}_{m,j}(\theta_o-\theta^r_{m,j})+H_{g,m,j}-H_{a,m,j} \quad (3)$$

$$\rho V_{m,j}\frac{dX^r_{m,j}}{dt}=\dot{m}_{m,j}(X_o-X^r_{m,j})+L_{g,m,j}-L_{a,m,j} \quad (4)$$

$$Q_{m,l}=(1+1/COP_{m,l})\cdot H_{total,m}\cdot IP_{m,l} \quad (5)$$

where $\theta^r_{m,j}$ (°C) is the room j's temperature in the type m of building; $X^r_{m,j}$ (g/kg(a)) is the room j's specific humidity in the type m of building; $V_{m,j}$(m^3) is the room j's volume in the type m of building; $A_{m,i,j}$(m^2) is the area of the i-th interior wall in room j in the type m of building; $\theta^w_{m,i,j}$ (°C) is the surface temperature of the i-th interior wall in room j and in the type m of building; X_o(g/kg(a)) is the specific humidity of outdoor air; $\dot{m}_{m,j}$ (kg/h) is the mass flow rate of fresh air of the room j in the type m of building; $H_{g,m,j}$(W) is the heat production of internal staff and lighting of room j in the type m of building; $H_{a,m,j}$(W) is the cooling load of room j in the type m of building by air conditioning; $L_{g,m,j}$(g/h) is the internal moisture gain of room j in the type m of building; $L_{a,m,j}$(g/h) is the moisture load of room j in the type m of building by air conditioning; $Q_{m,l}$(W) is heat exhaust of the l type air-conditioning system in the type m of building; $H_{total,m}$(W) is air conditioning total heat load in the type m of building; $COP_{m,l}$ is the energy efficiency of refrigeration unit of the l type air-conditioning system in the type m of building; $IP_{m,l}$ is the load correlation coefficient of the l type air-conditioning system in the type m of building.

Calculation of outdoor solar radiation

The calculation of the solar radiation is affected by various factors as: the building scale, layout, orientation, and the underlying surface reflectivity and so on. In this study, the model uses the ray tracing method to calculate the face-to-face shape factor(Zhu et al., 2007), the tiny surface emitted light along the upwardly hemisphere direction as shown as Figure 2.

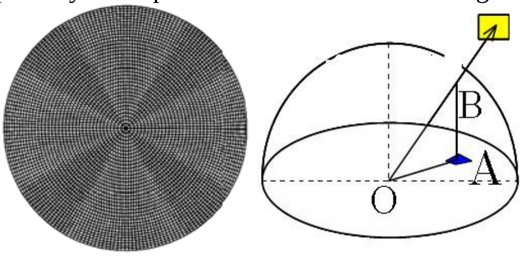

Figure 2 Calculation method for view factor (left: division of unit circle; right: direction of light beam)

For a tiny surface element *k* of a building wall or the ground, the heat balance equation is:

$$R_{n,k} = R_s \downarrow - \varepsilon_k \sigma \theta_k^4 + \varepsilon_k \left(F_{ks} \underset{k \neq p}{R_l} \downarrow + \sum_{p} \underset{k,p \neq s}{F_{kp}} \varepsilon_p \sigma \theta_p^4 \right)_s \quad (6)$$

where $R_s \downarrow$ and $R_l \downarrow$ (W/m^2) are respectively the downward shortwave and long wave radiation; ε_k and ε_p are the long wave reflectivity of the face *k* and face *p*; $F_{k,p}$ is the shape factor of face *k* to face *p*.

SIMULATION AND RESULT ANALYSIS OF THE THERMAL CLIMATE OF AN URBAN COMPLEX

The simulation condition and information

In this study, an actual urban complex planning project in the hot summer and cold winter zone of China is selected as the simulation object. The total area of civil buildings is about 1.14 million m^2 in the whole planning project land, Figure 3 shows the land functional status in this planning area. There are mainly five types of buildings in this area: office buildings, commerical buildings, residential buildings, entertainment buildings and eduction buildings.

Figure 3 Situation of land use in this planning area

The entire calculation period is the typical summer month (28 days) and the meteorological data is shown as Figure 4. The average outdoor temperature exceeds 28^{o}C and the maximum temperature exceeds 30^{o}C in the daytime; and the outdoor specific humidity during the whole calculation period maintained at a high level except for individual dates, and the average relative humidity is 78%. The average daily solar radiation intensity of horizontal plane is 177 W/m^2 and the maximum is 309 W/m^2 in the entire calculation period. In summary, this region shows a high temperature, high humidity, strong solar radiation during the calculation period.

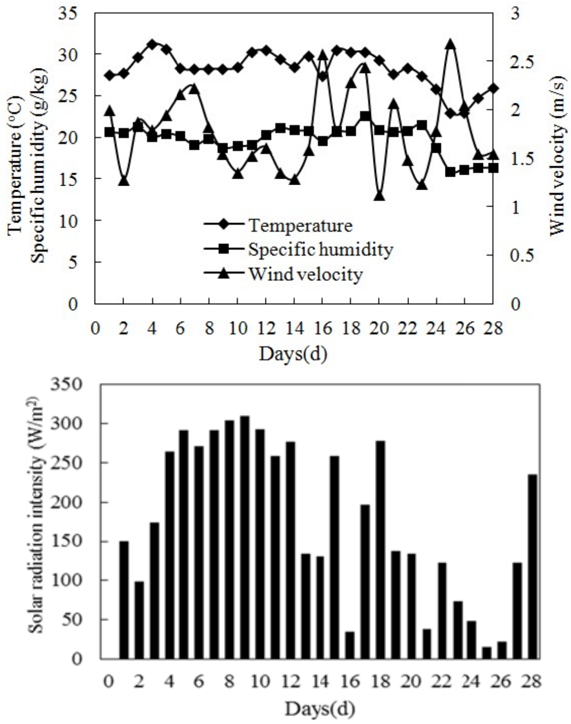

Figure 4 Meteorological data of the typical month in summer

Here, the irregular distribution of buildings is simplified as the square shape buildings in the regular layout, and land-use ratio of the various underlying surface are as follows: building is 44.2%, impervious artificial surface is 18.8%, lawn is 19.8%, tree is 13.2% and water is 4.0%. During the simulation, the envelope thermal parameters of different types of building and the air conditioning system set parameters are all refer to the local building energy efficiency design standards. The main calculation conditions are summarized in Table 1 shown as follows:

Analysis of the dynamic thermal balance in urban complex

The outdoor space is a relatively open space that is very different from the indoor environment. In this study, the heat balance and conversion is analyzed in this hypothetical closed space. As shown in Figure 5, in this imaginary closed space, the top of surface boundary-layer as the upper boundary, and the left and right boundary is properly established according to the area of urban.

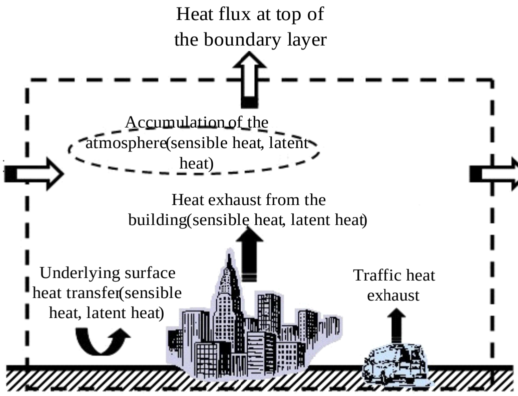

Figure 5 Diagram of urban canopy layer heat balance

Since the external meteorological parameters of the closed space is difficult to determine, and difference of temperature and specific humidity of the left and right side of the boundary is small, and relative to the large area of the upper and lower horizontal boundary, both the left and right sides of the boundary area is so small, therefore, this model does not consider the heat flows through the left and right boundaries. The ultimate impact factors of the thermal climate in this enclosed space mainly include the following six parts: heat exhaust from the underlying surface, heat exhaust from buildings air conditioning system, heat exhaust from the building ventilation system, heat exhaust from the traffic, heat flux at the top of the boundary layer, and heat storage of the atmosphere.

By using the established thermal climate prediction model of urban complex, the hourly variation of heat emission in a typical day and diurnal variation of heat emission during the calculation month are shown in Figures 6, 7 and 8, and the cumulative heat in a unit area within the urban complex throughout the whole calculation period can be calculated is shown in Table 2. When the heat enters into this space, the value is set as positive; and when the heat leaves this space, the value is set as negative.

- Hourly variation of heat emission from the different type buildings during a typical day

Figure 6 shows that the hourly variation of total heat emission from the different types of buildings is consistent with the air conditioning running time. Such as the heat emission from office building in the daytime as its air conditioning system is running from 08:00-18:00, however there almost no heat emission at other times. And the total latent heat emission from all buildings is significantly larger than the total sensible heat emission due to the buildings with evaporative cooling equipment account for the majority of the total number of buildings in the urban complex.

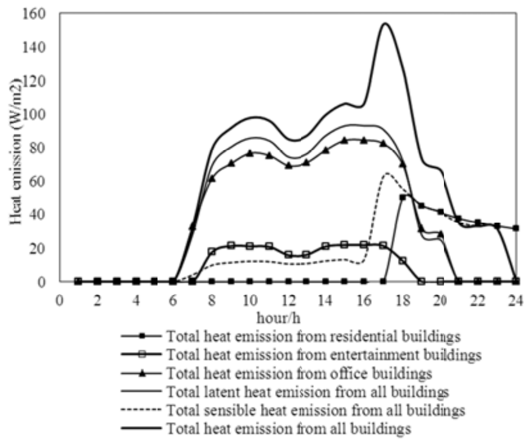

Figure 6 Hourly variation of heat emission from the different type buildings during a typical day

- Diurnal variation of heat emission from the different type buildings in the calculation month

Figure 7 and Table 2 shows that the sensible heat exhaust of the entire urban complex region mainly including: the sensible heat exhaust from the building air conditioning system and traffic, and the sensible heat exhaust from the underlying surface (such as roads, grass, trees, soil, water, etc.). In general, the sensible heat exhaust from the underlying surface is significantly greater than the other parts of the sensible heat exhaust, and its diurnal value changes apparently with weather conditions. While the sensible heat exhaust from the building air conditioning system and traffic changes slightly during the calculation period. By calculating the cumulative value of sensible heat exhaust during the entire calculation, it can be found that: the sensible heat exhaust from the underlying surface accounts for about 66.4% of the total sensible heat exhaust; the sensible heat exhaust from the building air conditioning system accounts for about 24.8% of the total sensible heat exhaust; the heat exhaust from the traffic accounts for about 8.7% of the total sensible heat exhaust. This shows that sensible heat exhaust from the underlying surface and building air conditioning system is the main causes of the formation of outdoor thermal climate, especially the former one is the most significantly influence factors.

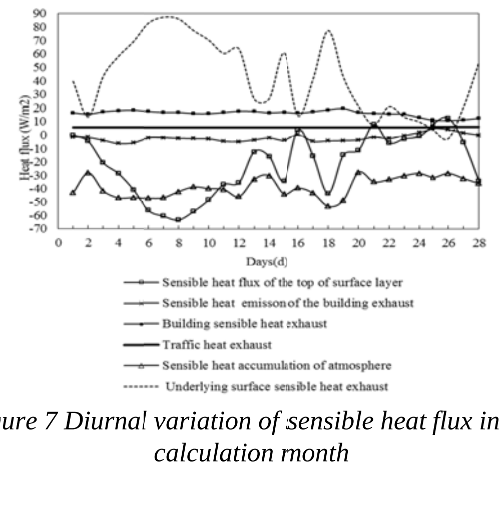

Figure 7 Diurnal variation of sensible heat flux in the calculation month

Figure 8 and Table 2 shows that the latent exhaust heat of the entire region mainly including: the latent heat exhaust from the building air conditioning system and the underlying surface (such as roads, grass, trees, soil, water, etc.). Since there are many public buildings use evaporative cooling equipment(such as cooling tower and so on) that exhaust a large amounts of moisture to the outside, the latent heat exhaust from the building air conditioning system is significantly greater than the other parts of latent heat exhaust, and it's diurnal value changes gently. By calculating the cumulative value of latent heat exhaust during the entire calculation, it can be found that: the latent heat exhaust from the building air conditioning system accounts for the largest proportion about 71.4% of the total latent heat exhaust. Followed by the latent heat exhaust from the underlying surface that accounts for about 28.4% of the total latent heat exhaust, this is because a large area of impervious artificial surface in this urban complex makes moisture transpiration greatly weakened.

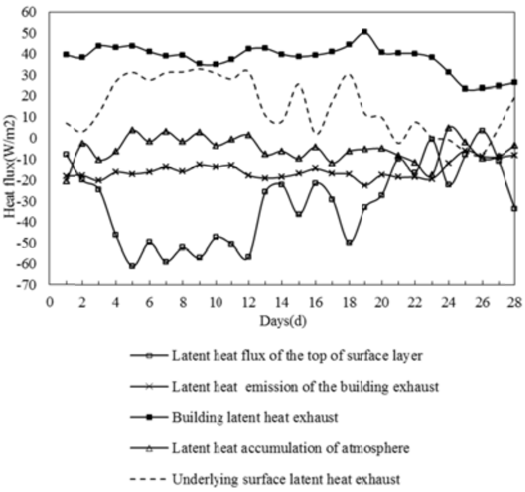

Figure 8 Diurnal variation of latent heat flux in the calculation month

Analysis the greening rate impact on the thermal climate of urban complex

The above dynamic thermal balance analysis in the urban complex shows that the heat exhaust from the underlying surface plays an important role in the formation of the thermal and humid climate of urban complex. Impervious artificial surface and urban greening system are two important parts of the urban underlying surface; both of them have completely different effects on the thermal climate of the urban compex. On the one hand, impermeable artificial surface absorb more solar radiation than greenbelt in the daytime. With the greater heat storage capacity, its surface temperature is significantly higher than greenbelt that release more heat into the atmosphere through convection heat transfer. On the other hand, urban greening system emission water vapour to the atmosphere through transpiration, and trees of urban greening system has shading effects; these all can reduce outdoor air temperature.

In this urban complex, the green land mainly includes trees and grass land, the heat flux calculation equations are as follows:

- Sensible heat flux H_t(W/m^2) and latent heat flux EV_t(W/m^2) of trees:

$$H_t = (6.79 + 5.99 \times U_{1.25})(T_{t,i} - T_{1.25}) \quad (7)$$

$$EV_t = A_t \alpha_w \beta_t (X_t - X_a) \quad (8)$$

Where $T_{t,i}$ (°C) is the surface temperature of trees; $U_{1.25}$ (W/s) and $T_{1.25}$ (°C) are respectively the wind speed and air temperature from the ground height of 1.5m; α_w (kg/m^2·s·(kg/kg)) is the moisture dissipation coefficient of the tree crown with the valve of 7.0×10^{-6}; β_t is the leaves group evaporation efficiency of the tree crown with the valve of 0.3; X_t (kg/kg) is the average moisture content of leaf surface; X_a (kg/kg) is the saturated moisture content of impervious artificial surface.

- Sensible heat flux H_g(W/m^2) and latent heat flux EV_g(W/m^2) of grass land surface:

$$H_g = (4.5 + 5.2 \times U_{1.25})(T_{g,i} - T_{1.25}) \quad (9)$$

$$EV_g = \kappa \cdot EV_s \quad (10)$$

$$EV_s = re_s (\varphi / \varphi_{sat}) \alpha_x (X_s - X_{1.5}) \quad (11)$$

Where $T_{g,i}$ (°C) is the grass surface temperature; κ is the ratio of land moisture dissipation flux of green land and soil; EV_s (W/m^2) is the latent heat flux of soil; re_s is the evaporation ratio, it's the function of weight moisture content ratio φ (kg/kg) and saturated moisture content ratio φ_{sat} (kg/kg); α_x (kg/m^2·s·(kg/kg)) is the mass transfer coefficient; X_s (kg/kg) is the saturated moisture content corresponding to a soil surface temperature; $X_{1.5}$ is the atmospheric moisture content from the ground height of 1.5m.

Based on the above heat flux model of the green land and established thermal predict model, the outdoor temperature change in urban complex can be analysed during the calculation period under the different conditions of impervious artificial surface and urban greening system. The increase of greening rate is achieved by a moderate reduction of the impervious artificial surface such as roads, parking lots, squares, etc.

As shown in Table 3, when the greening rate of this region increased from 0.33 to 0.35, the average outdoor temperature is reduced significantly by about 0.6°C, and when the greening rate of this region increased from 0.33 to 0.43, the average outdoor temperature is reduced significantly by about 1.0°C. Therefore, it's able to reduce the atmospheric temperature of urban complex by increasing the area of vegetation and reducing the area of impervious artificial surface, which could improve outdoor thermal comfort in turn.

CONCLUSIONS

An urban complex thermal climate prediction model with multi-type buildings is developed and applied in a southern actual planning project of China to simulate and analysis the thermal climate of it, the conclusions obtained are as follows:⑴By calculating the accumulated heat within the urban complex during the entire calculation period, the sensible heat exhaust from the underlying surface accounts for the largest proportion of the total sensible heat exhaust for about 66.4%, and the latent heat exhaust from the building air conditioning system accounts for the largest proportion of the total latent heat exhaust for about 71.6%, this shows the sensible heat exhaust from the underlying surface and the latent heat exhaust from the building air conditioning system are the main causes of the formation of outdoor thermal and humid climate.⑵By simulating the comparative examples, when the greening rate of this region increases from 0.33 to 0.35, the average outdoor temperature is reduced significantly by about 0.6^{o}C, and when the urban greening rate increases from 0.33 to 0.43, the average outdoor temperature is reduced by about 1.0^{o}C, which indicates that the thermal climate of the urban complex can be effectively improved by taking measures of increasing the urban greening rate.

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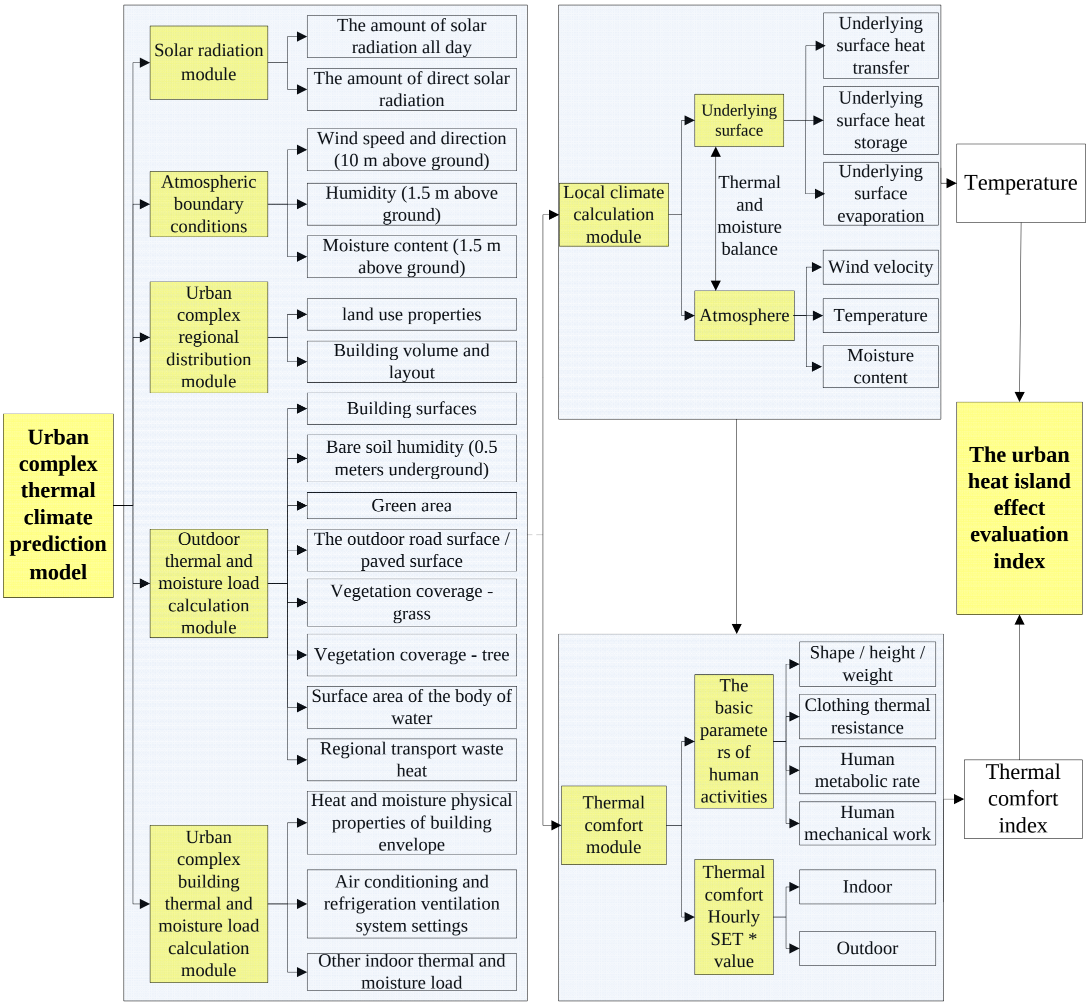

Figure 1 The framework of urban complex thermal climate prediction model

Table 1 Various types of building parameters and setting parameters of air conditioning system

BUIDING TYPE	BUIDING AREA (10^4 m^2)	AREA OCCUPIED PERCENTAGE (%)	FLOOR AREA RATIO	FRESH AIR FLOW RATE (m^3/h·p)	FORM OF A/C SYSTEM	A/C SYSTEM RUNNING TIME (h)
Residential	40.6	35.7	1.69	30	Split-type air conditioner	17:00—23:00
Office	43.1	37.8	3.79	30	Centrifugal chiller	08:00—18:00
Mall	10.8	9.5	3.98	20	Centrifugal chiller	09:00—21:00
School	7.2	6.3	0.90	14	Split-type air conditioner	08:00—19:00
Entertainment	12.3	10.8	1.00	25	Screw chillers	08:00—18:00

Table 2 The cumulative heat flux during the entire calculation within the imaginary closed space of the urban complex

	HEAT FLUX	CUMULATIVE VALUE (kWh/m^2)	PERCENTAGE (%)
Sensible heat flux	Heat exhaust from the underlying surface	1188.9	66.4
	Heat exhaust from the building air conditioning system	444.2	24.8
	Heat exhaust from the traffic	156.5	8.7
	Heat flux at the top of boundary layer	-637.9	-35.6
	Heat exhaust from the building ventilation system	-64.2	-3.6
	Heat storage of the atmosphere	-1087.5	-60.8
	Heat Balance	**0.0**	**0.0**
Latent heat flux	Heat exhaust from the underlying surface	421.1	28.4
	Heat exhaust from the building air conditioning system	1060.3	71.6
	Heat exhaust from the traffic	0.0	0.0
	Heat flux at the top of boundary layer	-882.4	-59.6
	Heat exhaust from the building ventilation system	-442.9	-29.9
	Heat storage of the atmosphere	-156.0	-10.5
	Heat Balance	**0.0**	**0.0**
Total heat flux	Heat exhaust from the underlying surface	1610.0	49.2
	Heat exhaust from the building air conditioning system	1504.4	46.0
	Heat exhaust from the traffic	156.5	4.8
	Heat flux at the top of boundary layer	-1520.3	-46.5
	Heat exhaust from the building ventilation system	-507.1	-15.5
	Heat storage of the atmosphere	-1243.6	-38.0
	Heat Balance	**0.0**	**0.0**

Table 3 The outdoor average monthly temperature at the different greening rates

GREENING RATE	IMPERVIOUS ARTIFICIAL SURFACE COVERGE RATE	TEMPERATURE (°C)	TEMPERATURE CHANGE (°C)
0.330 (base case)	0.188 (base case)	28.2	0.0
0.350	0.139	27.6	-0.6
0.430	0.090	27.2	-1.0