Predictive model for outdoor air temperatures of wooded communities

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[Abstract] Base on the principle of the Green CTTC model, we proposed a new predictive model for air temperatures of wooded communities. We conducted field studies in four communities in the hot and humid areas of China to obtain the key parameter and test the performance of the new model. Through field studies of the wooded communities with low-rise buildings, we found that the convective heat exchange ratio, i.e. the C value, was not constant. The C value increased in the morning and decreased in the afternoon, and the maximum could be reached 0.4. The new model with the obtained C value was verified through field studies of the wooded communities with high-rise buildings. The results show that the RMSE was less than 0.7 ºC and the consistency index was higher than 0.96 for the communities while the advective effect can be ignored, and the walls under height of 20m had great contribution to near-ground air temperature.

[Keywords] Outdoor air temperature, Green CTTC model, convective heat exchange ratio, wooded architectural complex

1. Introduction

The Green CTTC model developed by Shashua-Bar and Hoffman is based on the principle of the CTTC model and takes into account of thermal effects of trees. The model evaluates thermal effect of trees as the shade effect partly offset by the convective heat flow as follows:

$$\Delta t_{sol} = \sum_{i=0}^{\tau} \frac{m}{h} \Delta I_{pen} \left(1 - exp\frac{i-\tau}{CTTC}\right) \tag{1}$$

$$\Delta I_{pen} = \Delta I[1 - PSA_G - f(1-C)PSA_{Tr}] \tag{2}$$

$$f = \frac{I - I_v}{I} \tag{3}$$

$$C = \frac{Q_H}{I - I_v} \tag{4}$$

where Δt_{sol} is the contribution of solar radiation absorption to air temperature (℃), $\Delta I_{pen}$is the mean hourly variation of solar radiation absorbed by the cluster open space (W/m^2), m is the solar radiation absorptivity of surfaces, h is the overall heat transfer coefficient at surfaces (W/(m^2·K)), CTTC is the cluster thermal time constant (h), PSA_G and PSA_{TR} are the partial shaded area causing by buildings and trees, respectively, (1-*f*) is the solar radiation transmissivity of trees, C is the convective heat exchange ratio, I is the unobstructed solar radiation intensity (W/m^2), I_v is the solar radiation intensity under trees (W/m^2), Q_H is the convective heat exchange between trees and air (W/m^2).

The effect of convective heat exchange of trees on air temperature is counted in the same form of the solar radiation absorbed by ground, meaning that the effect reaches its steady state value gradually in a process that governed by the cluster thermal time constant. We denied this process and considered the convective heat flow of tree canopies produced an instantaneous increase of the ambient air temperature. Accordingly, we proposed a new Green CTTC model as follows, which calculates the cluster air temperature as the area-weighted average of the ambient air temperatures of ground, walls and trees:

$$\Delta t_{sol} = \frac{1}{A_G + A_W + A_T}\left\{A_G \sum_{i=0}^{\tau}\left[\frac{m_G \Delta I_G}{h}\left(1 - exp\frac{i-\tau}{CTTC_G}\right)\right] + A_W \sum_{i=0}^{\tau}\left[\frac{m_W \Delta I_W}{h}\left(1 - exp\frac{i-\tau}{CTTC_W}\right)\right] + A_T\frac{q_{c,T}}{h}\right\} \tag{5}$$

$$\Delta I_G = \Delta I_{DH}\left(1 - PSA_{W/G} - fPSA_{T/G}\right) + \Delta I_{dH} SVF_G \tag{6}$$

$$\Delta I_W = \Delta I_{DV}\left(1 - PSA_{W/W} - fPSA_{T/W}(\tau)\right) + \Delta I_{dV} SVF_W \tag{7}$$

$$q_{c,T} = I_{DN} f C \tag{8}$$

where A_G, A_W and A_T are the area of ground, floor and trees (m^2), m_G and m_W are the solar radiation absorptivity of ground and walls, $CTTC_G$ and $CTTC_W$ are the cluster thermal time constant of ground and walls (h), ΔI_G and ΔI_W are the mean hourly variation of solar radiation absorbed by ground and walls (W/m^2), $PSA_{W/G}$, $PSA_{W/W}$, $PSA_{T/G}$, $PSA_{T/W}$ are the partial shaded area on ground and walls causing by walls and trees, SVF_G and SVF_W are the sky view factor of ground and trees, ΔI_{DH}, ΔI_{dH}, ΔI_{DV}, ΔI_{dV} are the mean hourly variation of solar radiation absorbed by horizontal and vertical surfaces.

Only the direct solar radiation is considered in the original Green CTTC model, and both the direct and diffuse solar radiations are considered in the new model as Eq. (6) and (7) show. According to the new model, the key parameter, convective heat exchange ratio of C, can be determined by Eq. (9)~(12).

$$C = \frac{A_T q_{c,T}}{f[A_{TD} I_{DN} + A_T I_{dH} SVF_G]} \quad (9)$$

$$q_{c,T} = \frac{A_G + A_W + A_T}{A_T} h(\Delta t_{sol} - \Delta t_{B/G}) \quad (10)$$

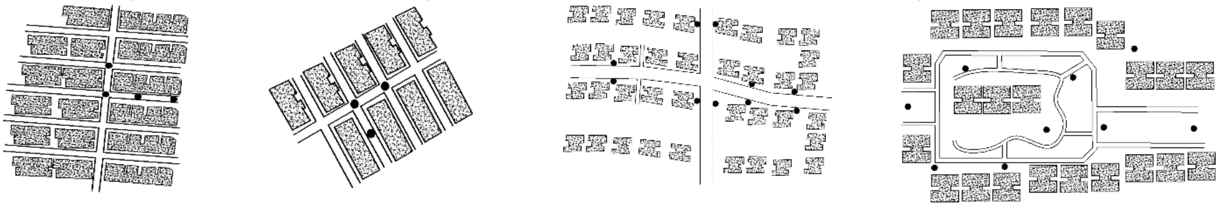
$$\Delta t_{sol} = t_a - t_b + \Delta t_{lw} \quad (11)$$

$$\Delta t_{B/G} = \frac{1}{A_G + A_W + A_T} \sum_{i=0}^{\tau} \left\{ A_G \left[\frac{m_G \Delta I_G}{h} \left(1 - exp \frac{i-\tau}{CTTC_G} \right) \right] + A_W \frac{m_W \Delta I_W}{h} \left(1 - exp \frac{i-\tau}{CTTC_W} \right) \right\} \quad (12)$$

The purpose of the present study is to obtain the key parameter and testify the performance of the new Green CTTC model through field studies in the wooded communities in the hot and humid areas of China.

2. Field studies

The field studies were carried out in four typical wooded communities in the hot and humid areas of China (Fig. 1). The buildings are low-rise (10m high) for community A and B and high-rise (90 m high) for community C and D. All the wall of buildings are covered with white or light-color ceramic tiles. The roads are 2m wide for community A, 5m for community B and 6m for community C. All the roads are covered with trees, grass and red bricks.



A B C D

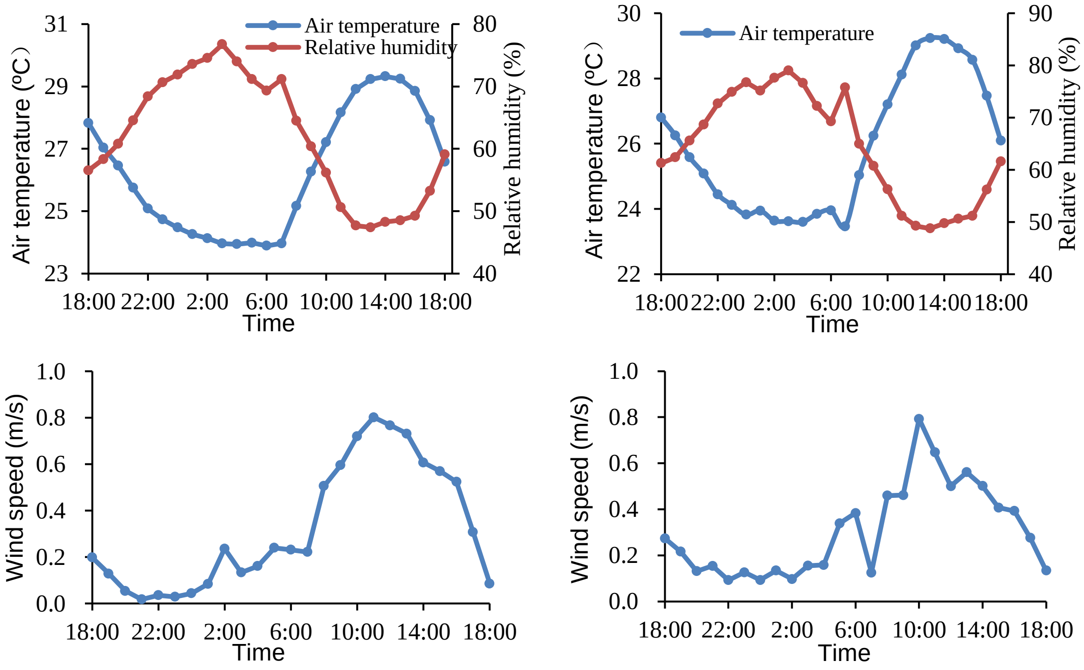
Fig. 1. The wooded communities in Guangzhou

The near-ground microclimates of community A, B and D were measured continuously in a summer sunny day, and the measurement of community C ran from 6:00 to 20:00 due to the interruption by rain. The measurement locations are shown in Fig. 1. The hourly data of the direct and diffuse solar radiations were obtained from the Guangzhou meteorological station.

3. Community A and B

3.1 Measurement results

The maximum of horizontal solar radiation was 780 W/m² during the measurement period of community A and B. The community microclimatic parameters were obtained by averaging all data of points weighted by their representative area. The daily microclimatic change of community A and B are shown in Fig. 2.



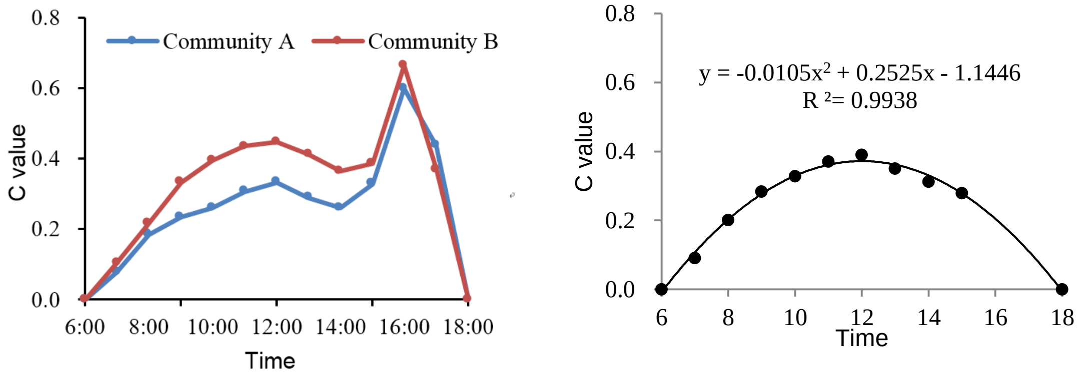
a Community A b Community B

Fig. 2. The daily microclimatic changes of community A and B

The daily mean air temperature of community A was 26.3 ºC, with a maximum of 29.3 ºC at 14:00 and a minimum of 23.9 ºC at 6:00. The relatively humidity changed in the opposite way of air temperature, and the daily mean, maximum and minimum were 60%, 75% and 46%, respectively. The wind speed was low at night and high in the daytime, and the daily mean was 0.3 m/s. For community B, the daily mean air temperature was 26.0 ºC with a maximum of 29.2 ºC at 13:00 and a minimum of 23.5 ºC at 7:00. The daily mean, maximum and minimum of relative humidity was 62%, 77% and 47%, respectively, and the daily mean wind speed was 0.34 m/s.

3.2 Determination of the C value

The C values for the time from sunrise to sunset were calculated by using the measured data of community A and B and the Eq. (8)~(10) as Fig. 3a shows. It can be seen that the change tendency of C value is similar for the two communities, that is to increase in the morning and decrease in the afternoon. A sudden increase of the C value was found around 16:00, which was caused by the abnormal sudden decrease of the solar radiation recorded by the metrological station. It was always sunny during the daytime of the field study, and therefore the data around 16:00 were removed and a well second order poly-nominal regression function was obtained for the C value while combining all data from the two communities as Fig. 3b shows. It can be known that the C value is 0 at time of sunrise and sunset, and reaches its maximum of 0.4 at noon. It is also indicated that the percentage of solar radiation that dissipated by convection can be as much as 40% for the trees.



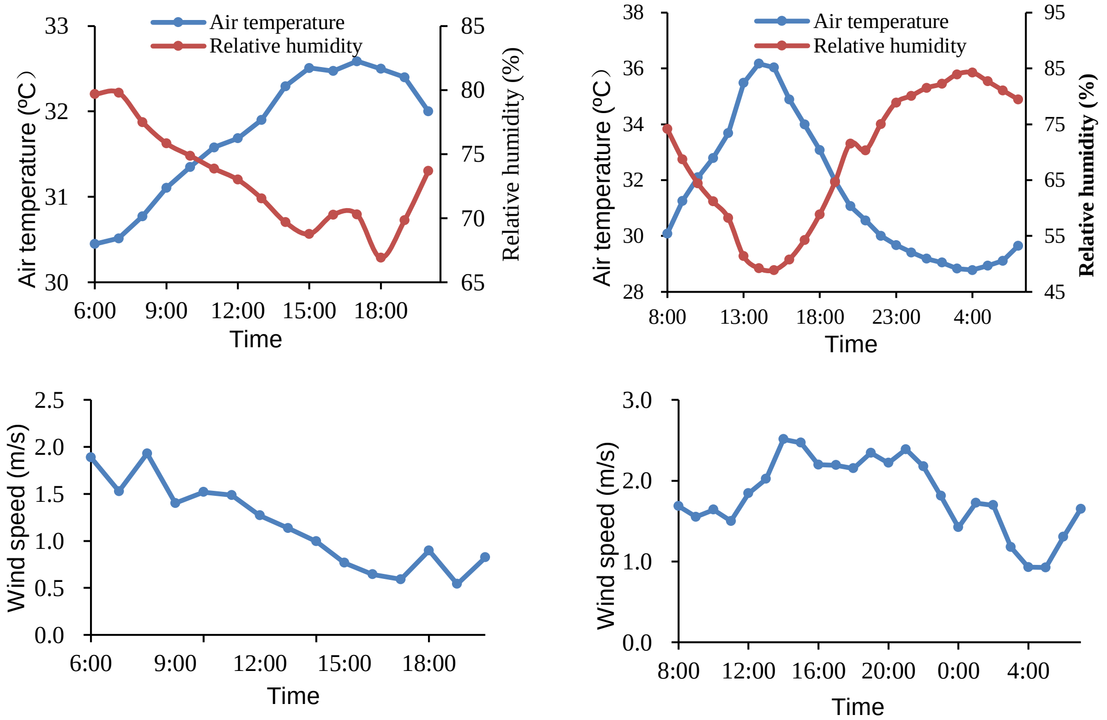
a The calculated results b The regression curve

Fig. 3. The C value

4. Community C and D

.4.1 Measurement results

. The maximum of horizontal solar radiation was 286 W/m² and 755 W/m² during the study period of community C and D, respectively. The community microclimates were obtained by the same way and the results are shown in Fig. 4.



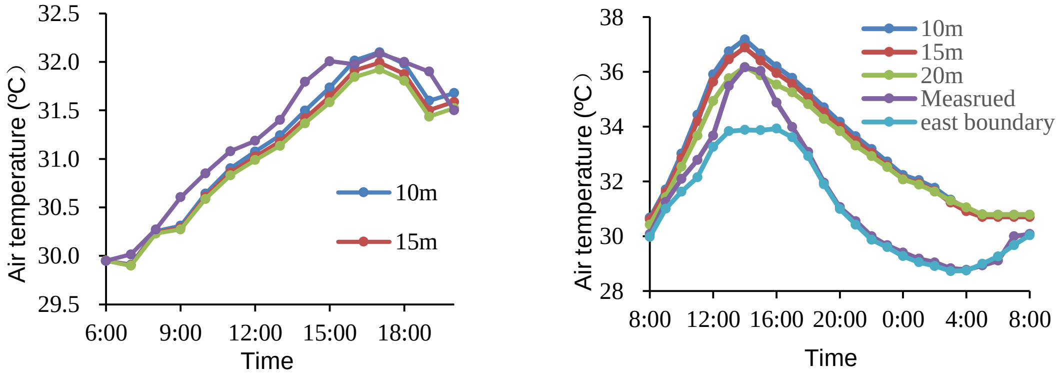
a Community C b Community D

Fig. 4. The daily microclimatic changes of community C and D

The air temperature of community C increased from 30.0 ºC to 32.1 ºC during 6:00-17:00 and then decreased. The relatively humidity changed in the opposite way to air temperature in a range of 70-79%. The wind speed decreased gradually from 1.9 m/s to 0.5 m/s. For community D, the daily mean, the maximum and the minimum were 31.4 ºC, 36.2 ºC, 28.8 ºC for air temperature, and 69%, 84%, 51% for relative humidity. The daily mean wind speed was 1.16 m/s and 1.31 m/s of community C and D, respectively.

4.2 Verification of the new model

The time changes of air temperature for community C and D were predicted by using the new model with the C values determined in Section 3.2. The predicted values were compared with the measured ones as shown in Fig. 5. The walls are very high in community C and D and a reasonable height of wall needs to be determined for near-ground air temperature calculation. The air temperatures were therefore predicted with three heights of walls, i.e., 10 m, 15 m and 20 m.



a Community C　　b Community D

Fig. 5. Predicted vs. measured air temperatures for community C and D

It can be seen from Fig. 5a that the predicted air temperatures are close to the measured ones for community C, and the predicted ones with various wall heights are not greatly different. The verification of the new model was further analyzed by RMSE and consistency index. The RMSE was less than 0.3 ºC and the consistency index was higher than 0.96 for all predictions, showing that the new model can predict well the time change of air temperature for community C.

The results for community D are different as Fig. 5b shows. The predicted air temperatures are close to the measured ones before 15:00, but become significantly higher after 15:00. The reason for the big difference after 15:00 is the strong advective heat exchange. The air temperature on the eastern boundary of community D is shown in Fig. 5b. It can be seen that the community air temperature changed with the boundary air temperature greatly due to the strong west wind in the afternoon. The CTTC models can not consider the effect of strong wind and advective effects, and so only the data before 15:00 were used to verify the new model. The results show that the RMSE was less than 0.7 ºC and the consistency index was higher than 0.97 for all the predictions. The results also show that the predictions with 20 m height of walls coincide with the measured ones most closely.

.5 Conclusion

Base on the principle of the Green CTTC model, we proposed a new predictive model for air temperatures of wooded communities, and we conducted field studies in four communities in the hot and humid areas of China to obtain the key parameter and test the performance of the new model.

Through field studies of the wooded communities with low-rise buildings, we found that the convective heat exchange ratio, i.e. the C value, was not constant. The C value increased in the morning and decreased in the afternoon, and the maximum could be reached 0.4. The new model with the obtained C value was verified through field studies of the wooded communities with high-rise buildings. The results show that the RMSE was less than 0.7 ºC and the consistency index was higher than 0.96 for the communities while the advective effect can be ignored, and the walls under height of 20m had great contribution to near-ground air temperature.

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