Environmental Engineering

Thermal comfort interventions of landscape elements in a humid and subtropical residential area in China

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\textbf{ABSTRACT}

This study aimed at revealing the subjective thermal comfort intervention of landscape elements in the humid and subtropical residential area of China. Data based on physical measurements and questionnaire surveys were collected. A new empirical model was developed according to microclimatic and subjective criteria, which considers air temperature, solar radiation, and wind speed. According to the empirical model in summer, a decrease of 84 W/m\textsuperscript{2} in global radiation or an increase of 0.35 m/s in wind speed would have the same effects on thermal perception as a drop of 1 °C in air temperature. A similar analysis could be conducted with the winter model, a change of 20 W/m\textsuperscript{2} in global radiation or a change of 0.10 m/s in wind speed have the same effects as a change of 1 °C in air temperature. Furthermore, the thermal comfort intervention of tree, shrubs, reflective surface and pervious ground were quantitatively analyzed based on the empirical model. We proposed that large broad-leaved trees and pervious ground were more conducive to the improvement of thermal acceptability during different seasons. The results showed that in summer, the total acceptable area significantly increased by 38.5%, whereas it was slightly reduced by 8.4% in winter.

\textbf{KEYWORDS}

Humid and subtropical area; residential area; landscape element; thermal comfort intervention; experience thermal comfort index

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\section{1. Introduction}

The urban microclimate, which impacts the perception and use of outdoor spaces such as time selection (Nikolopoulou and Lykoudis 2007; Lai et al. 2014a; Li, Zhang, and Zhao 2016), space selection (Nikolopoulou and Lykoudis 2007; Li, Zhang, and Zhao 2016), duration (Thorsson et al. 2007; Huang et al. 2016), and space acceptance rate (Lin et al. 2012; Lin 2009), is extremely important for the enjoyment of public spaces. Maximising outdoor space usage in summer is conducive to energy saving as indoor cooling demand can be reduced. Generally, urban microclimate and comfort are given little importance in the urban design and planning processes. However, many studies have highlighted how landscape elements in urban design and planning can improve outdoor microclimate and thermal comfort (Lai et al. 2019). According to several studies, the levels of radiation, wind speed, and air temperature in compact urban spaces are generally lower than those in open spaces, in terms of urban spatial geometry (Lai et al. 2019). These integrated effects can be evaluated using thermal indices. According to Andreou’s (2013) parametric analysis, the physiologically equivalent temperature (PET) values in compact spaces are found to be lower than those in open spaces at approximately 10 °C. Berkovic, Yeziro, and Bitan (2012) have dealt with courtyards and studied three different courtyards surrounded by a 9-m-high and 12-m-wide building and argued that the amount of shade is mainly affected by the courtyard orientation in hot dry climates. In addition, shade has the major role in improving the thermal comfort, while the contribution of wind is limited and much smaller than the shade contribution. Other studies have focused on urban canyons, which found that using trees in urban canyons is
very efficient in improving the thermal comfort (Ali Toudert and Mayer 2006; Johansson 2006).

Some studies have dealt with vegetation. Zheng, Zhao, and Li (2016) have investigated the influence of common subtropical tree species on the outdoor thermal environment, and argued that ficus microcarpa has the best cooling performance (reduced solar radiation by 1050 W/m², reduced mean radiant temperature (T_m) by 14.8 °C, reduced PET by 32.4 °C), but also have some negative effects: reducing wind speed (2.83 m/s) and increasing long wave radiation (55 W/m²). Yang and Lin (2016) have quantitatively evaluated the effect of trees, lawns, and grass bricks on the PET in the summer based on the simulation, and identified that trees are the most effective strategy for reducing the PET. Lee demonstrated that the average reduction in the PET by trees was 3.0 °C, whereas the average reduction by lawns was only 1.0 °C (Lee, Mayer, and Chen 2016). Furthermore, the influence of trees on human subjective perception was investigated (Yoshida et al. 2015), and the human heat load under the canopy of a tree was determined to be closer to neutral than that under the sun. The improvement in the thermal environment by a water body was usually considerably less than that provided by adding vegetation in summer. The reduction in the PET owing to the presence of a water fountain was only 1.4 °C (Chatzidimitriou and Yannas 2015). Regarding the subjective thermal environment evaluation of spaces with water bodies, a field survey conducted by Mahmoud (2011) in different spaces in an urban park in Egypt demonstrated that during hot months occupants in the lake zone were less dissatisfied than those in the other zones without a water body.

Research on the effect of pavements on the thermal environment has been mainly conducted with a focus on a reflective surface and pervious ground. Although reflective surfaces cool cities, many simulation studies show that pedestrian discomfort often increases because of the increased reflected solar radiation on the human body (Yang, Wang, and Kaloush 2015; Taleghani 2018). Yang, Wang, and Kaloush (2015) calculated an increase in thermal stress of up to 100 W/m² on pedestrians around noon under a high albedo scenario. The same conclusion could be reached by examining the PET values. In a simulation by Taleghani (2018), the PET increased by 6 °C at midday when albedo was raised by 0.4. As for pervious pavements, which with a high water absorption capability was beneficial to lowering the surface temperature and efficient in the mitigation of urban heat island effects (Wang et al. 2018).

The above studies have pointed out that local landscape elements have a direct impact on microclimate, which could be used to support the design decision of outdoor public spaces. However, the optimal allocation of landscape elements is not only based on the research of accurate quantification of microclimate, but also needs the evaluation index of microclimate. During the past decades, equivalent temperatures such as PET (Höppe 1999), standard effective temperature (SET*) (Gagge, Fobelets, and Berglund 1986), and universal thermal climate index (UTCI) (Bröde et al. 2012) were selected as evaluation indexes in most outdoor thermal comfort studies. The relevant index value can evaluate the objective change of the outdoor environment, but does not include the impact of users’ psychological (Nikolopoulou and Steemers 2003; Schweiker et al. 2013) and behavioral adaptations (Schweiker et al. 2013; Lin 2009), which have a significant impact on outdoor thermal comfort evaluation (Nikolopoulou and Steemers 2003; Lin 2009). The index value does not accurately reflect the residents’ subjective feelings of the outdoor thermal environment. If the applicability index which can accurately reflect residents’ thermal feelings of the intervention of landscape elements is selected to guide the design of landscape elements, which is more conducive to the improvement of thermal environmental quality.

These point to the need for a model to properly assess the thermal comfort perceived by the inhabitants. Therefore, this research focuses on the relationship between urban microclimatic variables and thermal perception. The hypothesis is that the prediction of thermal comfort in outdoor spaces requires a subjective approach for a given population adapted to certain climatic and cultural conditions. The goal is to propose an adaptive model or an empirical index to quantify the correlations between urban microclimatic variables and subjective variables (thermal perception). Although such empirical indices may be restricted to the geographical area or climate type, where the field survey was conducted, the advantage is its simplicity since does not require an iterative calculation. Likewise, the new model aims to predict the thermal comfort conditions of a population adapted to a given climatic condition, in this specific case, a metropolitan city in the hot and humid area of China. Based on this, the main objectives of this study are as follows.

(1) First, the thermal comfort in the residential area is investigated to develop the empirical thermal comfort indexes for evaluating the thermal comfort intervention of landscape elements in different seasons.

(2) Second, the thermal comfort intervention of different landscape elements is evaluated based on the empirical thermal comfort index.

(3) Finally, a comprehensive example of thermal comfort optimization of landscape elements is proposed for residential areas in the humid subtropical region of China.
2. Methodology

2.1. Climate and sites

This study was conducted in Guangzhou, a typical city in a humid subtropical area of China. Guangzhou is located in the south of China at a longitude of 112.8–114.2°E and latitude of 22.3–24.1°N. The annual mean air temperature and humidity of Guangzhou are 22 °C and 77%, respectively (Taleghani et al. 2015). The monthly mean air temperature varies slightly throughout the year, with a range of 13–29 °C (Figure 1). The monthly mean relative humidity is higher than 60% throughout the year. The daily mean air temperatures are 26–32 °C in July and 7–20 °C in January.

In the humid subtropical area of China, the enclosed and regular layouts are the most common in residential community planning (Li 2009). In particular, enclosed layouts are the development trend because of their adaptability to a humid subtropical climate (Li 2002). Therefore, in this study, we selected three enclosed-layout residential communities ("A", "B" and "C") and one regular-layout residential community ("D") as the study object, as shown in Figure 2. These four communities also present the representative features of the residential communities in the humid subtropical area of China: (1) they are all new high-rise residential communities that have been primarily built in the last decade; (2) they have a high population density, with more than 5000 residents in every residential community; (3) they have a greening rate greater than 30%, with some spots for outdoor activities. In this study, we were concerned with resting areas and focused on the two most popular activity spots in each residential community, as shown in Figure 2.

The field surveys were conducted at eight sites in four residential communities in Guangzhou. The main purpose of the field surveys was to collect the thermal perception of the residents under different urban microclimate which impacted by the local landscape elements. So, the survey sites were selected to capture a wide range of microclimate conditions. The considered factors include wind environment, direct solar radiation, reflection solar radiation and long wave radiation. Within the survey sites, areas with different microclimatic conditions (e.g. shaded, un-shaded, windy, wind-stagnant areas and so on) were identified and accounted for in the survey. The eight sites are shown in Figure 2. Sites 1, 3, 4 and 5 were well shaded by a tree, surrounding buildings and artificial shelters, whereas sites 2, 6, 7 and 8 were open areas to direct solar radiation and multiple solar reflections from neighboring buildings. Sites 5 and 7 also acted as the

Figure 1. Monthly mean air temperature (Ta (Mean)), maximum air temperature (Ta (Max)), minimum air temperature (Ta (Min)) and mean relative humidity (RH (Mean)) in Guangzhou. Data source: China Meteorological Administration, typical meteorological year data of Guangzhou (1971–2000) (Administration and University 2005).

Figure 2. Layout of the four residential communities and the survey spots.
corridor for wind, and sites 3, 4 and 6 were in the wind-stagnant areas.

2.2. Questionnaire survey

A questionnaire survey on outdoor thermal comfort and activities was conducted in this study. The first part of the questionnaire was used to collect information regarding demographic (i.e. age and gender), primary activity times throughout the day in outdoor spaces, reasons for visiting a particular place, clothing worn and activity level. The second part comprised questions for subjects to rate their current thermal sensation, thermal comfort, and thermal acceptability. The 9-point scale (ISO 1995) was used for thermal sensation, and the conventional 4-point scale (ISO 1995) was used for thermal comfort and acceptability (Figure 3). Finally, subjects were asked to indicate their preferences for air temperature, sun, wind, and relative humidity (Figure 4). The questionnaire survey was conducted during January–September 2015, in the winter and summer seasons. Table 1 summarizes the questionnaire survey schedule for 18 days. The surveys were conducted during the time frames of 8:00–12:00 and 14:00–18:00 in winter and 7:00–12:00 and 15:00–19:00 in summer, when the outdoor space was more frequently used. All field surveys were conducted on days with suitable weather to avoid windy or rainy conditions.

Figure 3. Thermal sensation, thermal comfort and thermal acceptability rating scales.

Figure 4. Preference rating scales.

Table 1. Schedule for questionnaire surveys.

| Season  | Time               | Residential communities | Sample size | Physical measurements | Questionnaire survey |
|---------|--------------------|-------------------------|-------------|-----------------------|----------------------|
| Winter  | Jan 10 and 19      | A                       | 305         | 8:00–19:00            | 8:00–12:00 and 14:00–18:00 |
|         | Jan 17 and 28      | B                       |             |                       |                      |
|         | Jan 25 and Feb 2   | C                       |             |                       |                      |
|         | Jan 22 and Feb 8   | D                       |             |                       |                      |
| Summer  | Jun 20, Aug 22, and Sep 6 | A                  | 484         | 7:00–20:00            | 7:00–12:00 and 15:00–19:00 |
|         | Jun 27, Aug 6, and Sep 11 | B                  |             |                       |                      |
|         | Jun 28 and Aug 19  | C                       |             |                       |                      |
|         | Jun 22 and Aug 2   | D                       |             |                       |                      |
days. Each activity spot was visited once in an entire day in each season, and two spots were surveyed twice in summer. We obtained 789 valid questionnaires: 305 in winter and 484 in summer.

2.3. Physical measurements

The physical parameters (i.e. air temperature (Ta), relative humidity (RH), global radiation (G), wind speed (v) and global temperature (Tg)) next to the interviewee were measured during the questionnaire surveys. All instruments were compliant with the ISO 7726 (ISO 1998) standard (Table 2) and placed at a height of 1.1 m above the ground, which is the recommended height of sensors for standing subjects according to ISO 7726 (ISO 1998). This height represents the center of gravity for the human body. The air temperature and humidity probes were shielded from solar radiation with forced ventilation. On the measurement day, the microclimate parameters were acquired at 1-min intervals during 8:00–19:00 in winter and 7:00–20:00 in summer (Table 1). To determine the $T_{mrt}$, the following formula was used:

$$T_{mrt} = \left[ \left( \frac{T_g + 273.15}{T_a} \right)^4 + \frac{1.10 \times 10^4 V_{a}^2}{\pi D^4} \right]^{0.25} - 273.15$$  \hspace{1cm} (1)

Where: $T_g$ is the global temperature (°C), $V_a$ is the wind speed (m/s), $T_a$ is the air temperature (°C), D is the globe diameter (m) and e is the globe emissivity.

### Table 2. Metrological properties of instruments used.

| Physical quantity | Instrument       | Range          | Accuracy          |
|-------------------|------------------|----------------|-------------------|
| Air temperature   | HOBO Pro V2 U23-001 | −40–70 °C | ±0.2 °C          |
| Relative humidity | HOBO Pro V2 U23-001 | 0–100%       | ±2.5%             |
| Global temperature| HD32.3           | −10–100 °C    | ±0.5 °C          |
| Wind speed        | HD32.3           | 0–5 m/s       | ±0.05 m/s (0–1 m/s) ±0.15 m/s (1–5 m/s) |
| Global radiation  | LP 471 PYRA 02.5 | 0–2000 W/m²   | ±3%               |

Figure 5. Hourly mean air temperature, relative humidity, wind speed and global radiation in both seasons.
3. Field measurement results

3.1. Outdoor thermal environment

The hourly mean air temperature, relative humidity, wind speed and global radiation of the outdoor spaces of the residential communities during the survey period were calculated in both seasons, and their changes are shown in Figure 5. The ranges of air temperature were 15.1–22.0 °C in winter and 27.9–37.2 °C in summer. The maximum air temperature occurred at 14:00 in both seasons. The hourly mean relative humidity changed inversely to air temperature in both seasons, with the ranges of 41.1–59.0% in winter and 39.9–87.2% in summer. The relative humidity was higher in summer (62.1% on average) and lowest in winter (45.6% on average). The wind speed remained at an average level of 0.7 m/s in both seasons. The global solar radiation in summer was stronger than that in winter.

The $T_{mrt}$ and PET were calculated and shown in Figure 6. The hourly changes of $T_{mrt}$ and PET were consistent with those of global solar radiation in both seasons. The $T_{mrt}$ ranged from 16.2 to 32.1°C in winter and 28.8 to –48.9 °C in summer. The PET ranged from 14.0 to 22.5°C in winter and 28.5 to –42.6 °C in summer. The hourly mean PET at the measurement locations in both seasons partly exceeded those in environments that were considered to be comfortable for humans in Guangzhou, which was found to be 18.1–31.1 °C (Li, Zhang, and Zhao 2016). Accordingly, further simulations will be performed with the goal of determining how to balance the comfort level in winter and summer.

3.2. Thermal sensation votes and sources of discomfort

Figure 7 shows the frequency distribution of the thermal sensation votes for both seasons. In winter the most frequently perceived thermal sensation was “Neutral” (34.4%), and the “Cool”, “Cold” and “Very cold” votes had few occurrences, with a total of 4.0%. The percentage of “Neutral” votes was generally higher in winter (34.4%) than in summer (20.2%), which suggested that people feel more comfortable thermally in winter than in summer. In summer, the percentage of people who felt “hot” was dominant (43.9%).
4. Experience thermal comfort index

4.1. Proposed adapted model

To evaluate the thermal comfort intervention of landscape elements according to climatic and subjective criteria in summer and winter, the “experience thermal comfort index for a residential area in the humid subtropical area of China (ETCIRC)” was developed. This was based on the linear regression between the thermal sensation votes (TSV) and urban outdoor thermal environment variables. The first step in the development of the ETCIRC was the selection of the most significant parameters. Spearman correlation test was used to study the correlations between thermal sensations and each of the environmental parameters (Table 3). Spearman correlation coefficient (r) is a non-parametric measure of the strength and direction of the association between two variables. The value of r ranges between −1 and 1, and a higher absolute value indicates a stronger association.

The highest coefficient was for the solar radiation (G) in both seasons, with 0.799 in winter and 0.686 in summer, indicating that there was a positive linear relationship between variables, as well as the global temperature (Tg) and T_mrt. Air temperatures (Ta) had correspondingly higher and positive linear correlations in both seasons. Wind speed (v) was found to have a significant negative relationship with thermal sensations and the correlation with relative humidity (RH) was not very high. Furthermore, the extent of the influence of relative humidity changed with the season, with a positive coefficient in summer and a negative coefficient in winter.

| Environmental parameters | V   | Ta  | RH  | Tg  | T_mrt | G     |
|--------------------------|-----|-----|-----|-----|-------|-------|
| (Correlation coefficient, r) | Winter | −0.793 | 0.705 | −0.297 | 0.684 | 0.617 | 0.799 |
|                          | Summer | −0.453 | 0.646 | 0.473 | 0.673 | 0.654 | 0.686 |

Figure 8. Percentage distribution of preference for thermal environmental factors of overall discomfort.
4.2. Definition of thermal comfort range

In addition, regression analysis was used to determine the relationship between thermal sensation vote and thermal unacceptability rate vote (TURV) in each season, as shown in Equations (4) and (5). The p values of the significance test of the regression models in winter and summer were both 0.000. ASHRAE standard 55 specifies that a good thermal environment setting must achieve 90% thermal acceptability (10% heat unacceptability) (ASHRAE 2004). According to the equations, the range of 10% heat unacceptability TSV values were 0.2 ≤ TSV ≤ 1.3 in winter and TSV ≤ 1.9 in summer. Therefore, in the process of outdoor thermal environment design, a warm outdoor environment should be created in winter, such that the TSV value of the outdoor space in winter is ≥ 0.2. In summer, a cool outdoor space should be created to make the TSV value of the outdoor space ≤ 1.9.

Winter: \[ \text{TURV}_w = 41.67 \text{TSV}^2 - 282.78 \text{TSV} + 64.37 \quad (R^2 = 0.83) \] (4)

Summer: \[ \text{TURV}_s = 33.14 \text{TSV} - 53.18 \quad (R^2 = 0.79) \] (5)

5. Thermal comfort intervention of landscape elements

5.1. Determination of intervention area

The D residential area (as shown in Figure 9) was selected to study the thermal comfort intervention of landscape elements. The residential area is a regular layout in the humid subtropical areas of China, covering an area of 119,600 m² and a total construction area of 477,800 m². The green area rate of the residential area was 35%. A series of outdoor spots were set for residents to engage in outdoor activities, such as spots 2, 3, 4, 9, 10, 11 and 12 in Figure 9. In this study, spot 4 in the children’s playground had the highest utilization rate and was selected for the optimal allocation of outdoor activity space landscape elements.

The children’s playground is a semi-enclosed area located on the southeast corner of the residential area, covering an area of approximately 4,000 m². To the north of the site is a plate-type high-rise residential building with a height of 92.6 m. To the west of the activity site is a plate-type residential building with a height of 95.6 m. A passageway is set between the two high-rise buildings to connect the children’s playground to the inner ring road and the centralized green space of the residential area. The setting of the
passageway also makes it easy for the children in the residential area to use the playground. The underlying surface of the playground is dominated by grass, shrubs, and pavement. The evergreen species *ficus microcarpa* are planted locally; they have seedlings with a height of approximately 4 m and a crown diameter of approximately 3 m. The main activity areas in the playground are the elliptical frame area and three circular sports equipment areas, as shown in Figure 10. Among them, the elliptical frame area is paved with red cement brick, the circular area is paved with green plastic, and the traffic lane in the children’s playground is paved with a red cement brick. The channel connecting the central activity node is paved with white cement mortar.

![Figure 10. Main activity areas of children’s playground.](image1)

![Figure 11. Ground profiles of children’s playground.](image2)

| Material          | Conductivity (W/m·K) | Specific heat (J/kg·K) | Density (kg/m³) | Albedo |
|-------------------|----------------------|------------------------|-----------------|--------|
| Concrete          | 1.96                 | 920*                   | 2159            | 0.30   |
| Red cement brick  | 1.81                 | 1050*                  | 2069            | 0.30   |
| White ceramic tile| 2.04                 | 1050*                  | 2285            | 0.50   |
| Cement mortar     | 0.93*                | 1050*                  | 1800*           | 0.30   |
| Green plastic     | 0.17                 | 1470                   | 600             | 0.20   |
| Sand              | 0.58                 | 1010*                  | 1600            | 0.20   |

The values with * are taken from the China national thermal design code (Ministry of Construction of the People’s Republic of China 2016); the remaining values are from the literature (Yang and Tao 2015).
Table 5. Intervention scenario in summer.

| Scenario | Setting | Remarks |
|----------|---------|---------|
| A1       | Current conditions |          |
| A2       | Grass replaced by shrubs |          |
| A3       | Paving materials inside the playground improved reflectivity | Reflectivity increased to 0.5 |
| A4       | Paving materials for the entire residential area improved reflectivity |          |
| A5       | Paving materials inside the playground increased water permeability |          |
| A6       | Paving materials for the entire residential area increased water permeability |          |
| A7       | Ficus microcarpa seedlings became 10-m tall trees | 3 m (height under branch), LAD* = 1.2 m²/m³ |
| A8       | Ficus microcarpa seedlings became 15-m tall trees |          |

Table 6. Intervention scenario in winter.

| Scenario | Setting | Remarks |
|----------|---------|---------|
| A1       | Current conditions |          |
| A2       | 10-m tall trees with LAD = 1.2 m²/m³ |          |
| A3       | 10-m tall trees with LAD = 0.6 m²/m³ |          |
| A4       | 10-m tall trees LAD = 0.2 m²/m³ |          |
| A5       | Grass replaced by shrubs with LAD = 1.2 m²/m³ |          |
| A6       | Grass replaced by shrubs with LAD = 0.6 m²/m³ |          |
| A7       | Paving materials for the entire residential area improved reflectivity | Reflectivity increased to 0.5 |
| A8       | Paving materials for the entire residential area increased water permeability |          |

Ceramic tile. The structures of the underlying surfaces are shown in Figure 11, and their physical properties are shown in Table 4.

5.2. Development of intervention scenario

To analyse the key aspects of landscape element design for the thermal comfort demand of residents, different strategies were listed. The summer conditions are shown in Table 5: current conditions (Scenario A1); grass in the playground replaced by shrubs (Scenario A2); paving materials of the playground improved reflectivity to 0.5 (Scenario A3); paving materials of the entire residential area improved reflectivity to 0.5 (Scenario A4); paving materials of the playground increased water permeability (Scenario A5); paving materials of the entire residential area increased water permeability (Scenario A6); Ficus microcarpa seedlings became 10-m tall trees (Scenario A7); Ficus microcarpa seedlings became 15-m tall trees (Scenario A8).

The winter conditions were proposed on the basis of the summer conditions, and it is shown in Table 6: current conditions (Scenario A1); Ficus microcarpa seedlings became 10-m tall trees with leaf area density (LAD) of 1.2 m²/m³ (Scenario A2); Ficus microcarpa seedlings became 10-m tall trees with LAD of 0.6 m²/m³ (Scenario A3); Ficus microcarpa seedlings became 10-m tall trees with LAD of 0.2 m²/m³ (Scenario A4); grass in the playground replaced by shrubs with LAD of 1.2 m²/m³ (Scenario A5); grass in the playground replaced by shrubs with LAD of 0.6 m²/m³ (Scenario A6); paving materials of the entire residential area improved reflectivity to 0.5 (Scenario A7); paving materials of the entire residential area increased water permeability (Scenario A8).

Table 7. Initial settings of ENVI-met model for summer and winter.

| Setting data | Summer | Winter |
|--------------|--------|--------|
| Simulation time Building | 5:00–20:00 | Wall K = 1.5 W/(m²-K); albedo = 0.3 |
|               |        | Roof K = 0.9 W/(m²-K); albedo = 0.3 |
| Initial temperature and relative humidity | Hourly average of different seasons derived from the typical meteorological years in Guangzhou | Wind direction with the highest frequency in different seasons |
| Wind direction | Wind speed in 10 m | Average value of maximum frequency wind speed |
| Wind speed in 10 m | 1.2 | 0.8 |
| Shortwave reduction ratio | 0.2–0.5 m: 307 K/40%; Below 0.5 m: 306 K/50% | 0.2–0.5 m: 296 K/40%; Below 0.5 m: 297 K/50% |
| Initial soil temperature and relative humidity | | |

...
ENV-met is a prognostic model for simulating urban and outdoor physical environmental interactions of heat, moisture, and particles, including ambient potential temperature, $T_{\text{mrt}}$, wind velocity and its direction (Bruse and Fleer 1998; Bruse 2009). ENV-met can be used in a variety of applications, including thermal adaptation strategies using vegetation (Srivanit and Hokao 2013; Yang et al. 2013), pavement materials (Yang et al. 2013; Carnielo and Zinzi 2013; Taleghani et al. 2014), type of soils (Yang et al. 2013; Chow et al. 2011), building layout (Berkovic, Yezioro, and Bitan 2012; Taleghani et al. 2015; Berkovic, Yezioro, and Bitan 2012), and site planning (Wang and Zacharias 2015; Frohlich and Matzarakis 2013). The newest version of the ENV-met 4.0 model was used in this study. This version not only allows the initial atmospheric temperature and relative humidity values, but also the air temperature and relative humidity values to be manipulated every hour in the function of “simple force.”
Figure 12. Simulated thermal environments under current conditions and following implementation of adjustment strategies in summer.

a) Current condition at 8:00
73.1% of the area; TSV > 1.9

b) Adjustment condition at 8:00
34.6% of the area; TSV > 1.9

c) Current condition at 18:00
31.5% of the area TSV > 1.9

d) Adjustment condition at 18:00
24.5% of the area TSV > 1.9

Figure 13. Simulated thermal environments under current conditions and following implementation of adjustment strategies in winter.

a) Current condition at 10:00
87.8% of the area TSV ≥ 0.2

b) Adjustment condition at 10:00
79.4% of the area TSV ≥ 0.2

c) Current condition at 16:00
47.9% of the area TSV ≥ 0.2

d) Adjustment condition at 16:00
45.5% of the area TSV ≥ 0.2
Thus, the simulated values approximated the measured values.

Table 7 presents the initial settings of the model in winter and summer. Roof albedo, wall albedo, roof insulation, and wall insulation were obtained according to the environmental conditions and building codes in Guangzhou, China (Ministry of Construction of the People’s Republic of China 2012). Soil temperature was obtained according to the test results for the humid subtropical area of China (Yang et al. 2013). The main differences in the data between summer and winter were in air temperature, wind speed, and wind direction derived from the typical meteorological years in Guangzhou (Administration and University 2005). The correction ratio of solar radiation was 1.2 in summer and 0.8 in winter, as verified in a previous study (Li 2017).

### 5.4. Quantitative analysis of intervention of different landscape elements in summer and winter

Occupants are the center of any landscape design. Outdoor activity spots in the residential communities were not used by residents at noon because they were in the habit of going home for lunch and taking a nap afterward (Li, Zhang, and Zhao 2016; Lai et al. 2014b). The activity time was affected by the daily life patterns of the residents. According to the questionnaire survey, in summer, the times of maximum attendance in the residential communities were the early morning (8:00–9:00) and evening (18:00–19:00). In winter, attendance reached maximum levels at midnight (9:00–11:00) and early afternoon (16:00–17:00). Therefore, the thermal environment at maximum attendance times is analysed. Tables 8 and table 9 present the simulated results of different scenarios in summer and winter, which are described in Section 5.2. The first line of every scenario is the range difference of each network node value $\Delta TSV(A_\chi - A_1)$, and the second line is the mean difference $\Delta TSV(\chi - 1)$. The orange table represents an increase in $TSV$ value, and the blue one represents a decrease.

According to the values of $\Delta TSV$ in different scenarios in summer, permeable ground (Scenarios A5 and A6) always cooled the thermal sensation, and with the increase in pervious ground area, the cooling effect increased. The high reflection ground (Scenario A3 and A4) always had the function of heating and with the increased high reflective surface area, the heating effect became stronger. However, the shrubs scenario (Scenario A2) and the trees scenario (Scenarios A7 and A8) had different functions in different time periods. When the solar radiation was weak at 18:00, 19:00, 20:00, and 7:00, the $TSV$ value of the shrubs scenario and tree scenario increased and the thermal acceptance reduced. When the solar radiation was strong at 8:00, 9:00, and 17:00, the $TSV$ value decreased and thermal acceptability increased. In addition, in trees scenarios, the 15 m tall trees scenario reduced $TSV$ more significantly when the solar radiation was strong, and the $TSV$ increased less under weak solar radiation.

The observed $\Delta TSV$ in different scenarios in winter, such as high reflection ground (Scenario A7) and permeable ground (Scenario A8), showed that the change in $TSV$ in the active area was similar to that in summer. The $TSV$ value of Scenario A7 increased and the thermal acceptable condition increased. The $TSV$ value in scenario A8 decreased and the thermal acceptable condition decreased. Under different LAD shrub scenarios, the $TSV$ and thermal acceptability in the active area increased and the improvement effect increased with an increase in the LAD. Under trees scenarios with different LAD values, when the solar radiation was strong at 8:00–11:00 and 15:00, the $TSV$ value was reduced compared with the original condition, the thermal acceptability in the active area was reduced, and in the rest of the time, the thermal

| City                     | Climate | Season     | Model                                            | $R^2$ |
|--------------------------|---------|------------|--------------------------------------------------|-------|
| Athens, Greece (Nikolopoulou, Lykoudis, and Kikira 2004) | Csa     | All year   | $TSV = 0.034Ta + 0.001G - 0.086V - 0.001RH - 0.412$ | 0.27  |
| Freiburg, Germany (Nikolopoulou, Lykoudis, and Kikira 2004) | Cfb     | All year   | $TSV = 0.068Ta + 0.0006G - 0.107V - 0.002RH - 0.69$ | 0.68  |
| Kassel, Germany (Nikolopoulou, Lykoudis, and Kikira 2004) | Cfb     | All year   | $TSV = 0.043Ta + 0.0005G - 0.077V - 0.001RH - 0.876$ | 0.48  |
| Cambridge, England (Nikolopoulou, Lykoudis, and Kikira 2004) | Cfb     | All year   | $TSV = 0.113Ta + 0.0001G - 0.05V - 0.003RH - 1.74$ | 0.57  |
| Sheffield, England (Nikolopoulou, Lykoudis, and Kikira 2004) | Cfb     | All year   | $TSV = 0.07Ta + 0.0012G - 0.05V - 0.003RH - 0.855$ | 0.58  |
| Curitiba, Brazil (Kruger and Rossi 2011) | Cfb     | Winter, Spring, Summer | $TSV = 0.13Ta + 0.0007G - 0.27V - 2.31$ | 0.455 |
| Mendoza, Argentina (Ruiz and Correa 2015) | BWb     | Summer, Winter | $TSV = 0.0621Ta - 0.3257V + 0.0079RH - 0.9796$ | 0.72  |
| Wuhan, China (Lai et al. 2014b) | Cfa     | Summer, Autumn | $TSV = 0.0643Ta + 0.0076G - 0.161V - 0.0037RH - 1.382$ | 0.67  |
| Hongkong, China (Cheng et al. 2012) | Cwa     | Summer, Winter | $TSV = 0.1185Ta + 0.0025G - 0.6019V - 2.47$ | 0.81  |
| Guangzhou, China         | Cfa     | Winter     | $TSV = 0.081Ta + 0.004G - 0.886V - 1.528$ | 0.79  |
|                          |         | Summer     | $TSV = 0.084Ta + 0.001G - 0.239V - 0.753$ | 0.63  |
acceptability in the active area was improved. With the decrease in the LAD, the deterioration effect decreased in the daytime, but the improvement effect at night decreased.

Comprehensive consideration of thermal comfort intervention under different scenarios in summer and winter showed that the surrounding trees should be tall and broad-leaved trees to improve outdoor thermal comfort. In summer, tall trees distinctly improved the thermal acceptability of the outdoor space during the daytime and the deterioration effect at night was relatively weak. With the passing of the seasons, in winter, trees lost their leaves and the leaf area density decreased which minimized the effect of thermal acceptability deterioration in the daytime. Shrubs can improve the thermal acceptability of outdoor spaces in winter, but the results showed that in summer when the solar radiation was weak, the setting of shrubs worsened the outdoor thermal acceptability. The high reflection ground deteriorated the thermal acceptability of the outdoor space in summer and improved the thermal acceptable condition of the outdoor space in winter. Permeable ground worsened the thermal acceptability of the outdoor space in winter and improved the thermal acceptability of the outdoor space in summer. Due to the long hot season in hot and humid areas of China, it is suggested to select permeable ground as the thermal environmental design strategy and to focus on improving the outdoor thermal comfort in summer.

5.5. Integrated optimized landscape element design proposed

This section details the optimal design of the outdoor space landscape elements. Combined with the quantitative evaluation of different landscape elements in summer and winter, the integrated optimal design of the outdoor thermal environment mainly considered the combination of tall broad-leaved trees and permeable ground. The leaf area density of broad-leaved trees was 1.2 m²/m³ in summer and 0.2 m²/m³ in winter. Figure 12 shows the thermal acceptability of the outdoor space in the main activity periods of 8:00 and 18:00 in summer after adding 10-m high trees and setting permeable ground. It was explained in Section 4 that cool outdoor space should be created in summer, which would make the thermal feeling range of outdoor space ≤1.9. From the statistics of the current conditions, it can be seen that in the main activity period, the TSV was greater than 1.9 (white area in the triangle) with 73.1% at 8:00 and 31.5% at 18:00. Compared with the current condition, the improvement strategy increased 38.5% of the acceptance area in the morning and increased 7% in the afternoon. After optimization, the range of acceptable areas increased significantly.

Figure 13 shows the outdoor thermal acceptability after adding 10-m high trees and setting permeable ground in the main winter activity periods of 10:00 and 16:00. In winter, a warm outdoor environment was created to make the TSV≥0.2. It can be seen that 87.8% of the areas TSV≥0.2 at 10:00, and with 47.9% at 16:00. Compared with the current condition, the total amount of acceptable area was reduced, but the reduction was very limited. In the morning, it was reduced by 8.4% and in the afternoon, it was only reduced by 2.4%.

6. Discussion

6.1. Outdoor thermal comfort evaluation model

The universal application of certain outdoor thermal comfort evaluation models has been debated. It is recognized that outdoor thermal comfort is not defined only by environmental parameters, clothing, and human activity. Human psychology also has a strong influence on the perception of comfort (Nikolopoulou and Steemers 2003; Schweiker et al. 2013). Therefore, it is important to include psychological adaptation parameters, namely naturalness, expectations, experience (short/long-term), time of exposure, and perceived control to predict outdoor thermal comfort (Nikolopoulou and Lykoudis 2006). From the analysis of this background, we propose a new empirical model of thermal comfort. This simple tool can be used to predict the thermal comfort conditions experienced by people in residential areas of Guangzhou, located in a humid subtropical area of China. Thus, urban planners have more elements to improve the design of outdoor spaces.

The empirical model of this study, and those obtained by others, are presented in Table 10. From the table, we can observe that all models developed in Europe (Nikolopoulou, Lykoudis, and Kikira 2004) have the same variables: air temperature, solar radiation, wind speed, and relative humidity. However, the coefficients of some of the variables, such as solar radiation, are very low and result in a low R² value. It is noticeable that in a tropical city such as Curitiba, where the humidity is high during the entire year, the model does not include the variable humidity (Kruger and Rossi 2011). It might be inferred that people have less sensibility to the variability of less modification variables for characterizing the local climate. This study is similar to that for Curitiba. The model in Wuhan (Lai et al. 2014b) China shows that relative humidity is a less important meteorological parameter affecting outdoor thermal comfort. In addition, the empirical models that were developed based on both summer and winter experiments in Hong Kong (Cheng et al. 2012), with or without humidity, demonstrated that the correlation coefficients between the measured and predicted
thermal sensation were significantly high (approximately 0.8 in both cases). However, the results showed the differences in predicted thermal sensation, with and without the inclusion of humidity in summer and winter, respectively. The inclusion of humidity marginally improved the prediction in summer (R² increased from 0.7029 to 0.7641), whereas its effect in winter was almost negligible.

According to the empirical index in summer, a decrease of 84 W/m² in global radiation or an increase of 0.35 m/s in wind speed would have the same effects on thermal perception as a drop of 1 °C in air temperature. A similar analysis could be conducted with the winter model, a change of 20 W/m² in global radiation or a change of 0.10 m/s in wind speed have the same effects as a change of 1 °C in air temperature. The quantitative results conformed to the result of sources of discomfort, weak sunshine and strong wind were associated with discomfort in winter and strong sunshine and weak wind in summer. From the comparison between winter and summer, it is shown that residents were more sensitive to wind speed and solar radiation in winter and a slight change can be perceived and cause different thermal perceptions. Because air temperature cannot be controlled easily in an outdoor environment, the blockage of solar radiation and the reduction or acceleration of wind speed were the only feasible ways to improve outdoor thermal comfort.

6.2. Intervention of landscape elements on thermal comfort in summer and winter

The results of the simulation described in Section 5.4 show that the adjustment strategies cooled and heated thermal sensation, and change according to season and time. The permeable ground had a cooling effect and reduced the TSV. The result is similar to a previous study (Nakayama and Fujita 2010), which showed that the thermal environment above the water-retentive pavement was cooler than that above the lawn and considerably lower than that above the building rooftop. Furthermore, the reflective surface absorbs less solar radiation and thus, has a lower surface temperature than traditional pavement. Cool materials reduce the temperature of the surface and decrease convective heat transfer from the surface to the air, thus producing cooler air temperatures than the traditional surface. Santamouris (2014) estimated the average air temperature reduction to be 0.3 K for every 0.1 increase in albedo. Although the reflective surface cooled the air temperature, the reflective surface was claimed to have a heating effect on the residential area throughout the year because of the increased reflected solar radiation on the human body. The same conclusion can be reached by examining the PET values. In a simulation by Taleghani (2018), the PET increased by 6 °C at midday when albedo was raised by 0.4.

The influence of greening on thermal comfort is complex, and changes with the seasons and hours. According to a study conducted by Oke et al. (2017), the addition of trees causes a smooth reduction in the wind. Furthermore, trees can remove a significant amount of incoming short-wave solar radiation. According to Brown and Gillespie, generally, only 10% of visible and 30% of infrared radiation is transmitted through trees (Brown and Gillespie 1995). The reduction of air temperature by trees has been studied by numerous researchers. de Abreu Harbich, Labaki, and Matzarakis (2015) reported that individual trees reduced the air temperature by 0.9–2.8 K between 10:00 and 14:00. In summary, at the time of strong solar radiation, trees have a cooling effect; with the gradual weakening of solar radiation, the wind speed attenuation becomes prominent, and the heating effect of trees appears. The impact of shrubs on the outdoor thermal environment is similar to that of trees. However, the effect of shrubs on solar radiation is limited. The main effect is the reduction of the wind speed and increase in the thermal effect.

Although the results of the simulation described in Section 5.4 showed that the adjustment strategies had a cooling or heating effect, in practice, various strategies must be applied simultaneously to produce these effects. In Section 5.5, an integrated strategy is proposed for reducing heat stress. Large broad-leaved trees and permeable ground are more conducive to the improvement of outdoor thermal comfort during different seasons in the hot and humid areas of China. The results showed that in summer, the total acceptable area significantly increased, and in winter, the total acceptable area slightly reduced.

7. Conclusions

This study recorded physical measurements and collected questionnaire surveys to obtain the experience thermal comfort index ETCIRC in the residential communities in a humid subtropical area of China. Based on the ETCIRC, thermal comfort interventions of different landscape elements were quantitatively analysed. The main conclusions are as follows.

(1) The percentage of “Neutral” votes was generally higher in winter (34.4%) than in summer (20.2%). In summer, the percentage of people who felt “hot” was dominant (43.9%). In winter, weak sunshine and strong wind were associated with discomfort. Whereas in summer, strong sunshine, lower wind speed and higher air temperature were sources of discomfort.
(2) The ETCIRC model considered three microclimate variables: air temperature, solar radiation, and wind speed. According to the empirical model in summer, a decrease of 84 W/m² in global radiation or an increase of 0.35 m/s in wind speed would have the same effects on thermal sensation as a drop of 1 °C in air temperature. A similar analysis could be conducted with the winter model, a change of 20 W/m² in global radiation or a change of 0.10 m/s in wind speed have the same effects as a change of 1 °C in air temperature.

(3) Based on quantitative analysis of intervention of different landscape elements in summer and winter, the results showed that the high-reflection ground deteriorated the thermal acceptable condition of the outdoor space in summer and improved the same in winter. Permeable ground worsened the thermal acceptability of outdoor space in winter and improved it in summer. In the case of vegetation, at the time of strong solar radiation, trees provided a cooling effect; with the gradual weakening of solar radiation, the wind speed attenuation became prominent, and the heating effect of trees appeared. The impact of shrubs on the outdoor thermal environment is similar to that of trees. However, the effect of shrubs on solar radiation is limited. The main effect is the reduction of the wind speed and increase in the heating effect.

(4) This study concludes that large broad-leaved trees and permeable ground are more conducive to the improvement of outdoor thermal comfort during different seasons in hot and humid areas of China. The results showed that in summer, the total acceptable area significantly increased by 38.5%, and in winter, the total acceptable area slightly reduced by 8.4%.

The ETCIRC will be useful to designers and urban planners, in order to estimate the degree of habitability in the humid and subtropical residential area in China. The recommended strategies will provide a common base toward creating standards to use in future studies regarding creating a comfortable microclimate in the humid and subtropical residential area in China. We wish to emphasize that the findings are not intended to be transferred to other climates and locales as thermal comfort is not only a matter of physiology, it relates psychologically to the values, lifestyle, behaviors, tolerance and acclimatization of people. This is the reason why we believe that, certainly at the moment, many surveys need to be conducted. Hopefully, one day, we can collate the data comprehensively and find a way to unify them.

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