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Evaluating the performance of different thermal indices on quantifying outdoor thermal sensation in humid subtropical residential areas of China

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Considerations of urban microclimate and thermal comfort are necessary for urban development, and a set of guidelines for a comfortable microclimate must be developed. However, to develop such guidelines, the predictive ability of thermal indices for outdoor thermal perceptions under different design decisions must be defined. The present study aimed to determine suitable indices for assessing outdoor thermal reaction in humid subtropical residential areas of China. Five criteria of coefficients of determination, Spearman's rho, percentage of correct prediction, percentage of thermal comfort indices' class predictions, and distribution of thermal comfort indices' class predictions per class of thermal sensation votes (TSV) were established to assess the performance of four thermal indices commonly used in outdoor thermal comfort research of China. The empirical thermal comfort index (TSV_{model}) had a better correlation with TSV, while the Universal Thermal Climate Index (UTCI) was the most successful, simulating 29.8% of TSV. The testability of Physiologically Equivalent Temperature (PET) and Standard Effective Temperature (SET*) were very low, with the correct predictive ability 16.5% and 24.4% respectively. In the selected indices, the UTCI reasonably approximated the observed data for this study and was recommended to assess the outdoor thermal comfort for evaluating the thermal comfort level under different design decisions. For all the indices, the systematic errors were

Abbreviations: PMV, Predicted Mean Vote [-]; SET*, Standard Effective Temperature [°C]; OUT_SET*, Outdoor Standard Effective Temperature [°C]; PET, Physiologically Equivalent Temperature [°C]; UTCI, Universal Thermal Climate Index [°C]; DI, Discomfort index [-]; CP, Cooling Power [W/m^2]; THI, Temperature-Humidity Index [°C]; Ts, Thermal Sensation [-]; TSV, Thermal Sensation Votes [-]; TSV_{model}, The empirical thermal comfort index [-]; T_{mrt}, Mean Radiant Temperature [°C]; Adu, Surface area of the unclothed body [m^2]; Ta, Air temperature [°C]; RH, Relative humidity [%]; G, Global radiation [W/m^2]; Tg, Globe temperature [°C]; D, Globe diameter [m]; ε, Globe emissivity [-]; M, Metabolic rates [W]; Clo, Clothing insulation [clo]; RMSE, Root mean square error [°C]; RMSEs, Systematic errors [°C]; RMSEu, Unsystematic errors [°C]; d, Index of agreement [-]; V_a, Wind speed at a height of 1.1 m above the ground [m/s]; V_{10m}, Wind speed at a height of 10 m above the ground [m/s].

generally higher than the unsystematic errors, indicating that the assessment scales do not adapt to humid subtropical residential areas of China. It is necessary to establish the thermal sensation ranges of humid subtropical areas of China.

KEYWORDS

humid subtropical area, thermal sensation votes, thermal comfort indices, assessment, performance

1 Introduction

Most of the world's population lives in cities and is continuously becoming more urbanized (United Nation, 2019). By the end of 2021, the urbanization rate of China was 64.7% (China Bureau of Statistics, 2021), indicating more than 914.2 million people lived in cities. In the context of Chinese reality, most urban population live in concentrated residential areas. The outdoor space of residential area is an organic part of the city, and their quality provides comfort and healthy surroundings to city dwellers (Du and Xia, 2018; He, 2022) and contributes to the energy efficiency of buildings (Yang et al., 2014; Li et al., 2021; Li et al., 2022). Consequently, the creation of attractive outdoor spaces is one of the main tasks of planning designer. However, at the design stage, planners and architects face difficulties in assessing the impact of different design concepts on people's perception. For the proposed difficulties, numerous thermal comfort indices have been developed to assess outdoor thermal comfort.

At present, commonly used thermal comfort indices for the valuation of outdoor thermal comfort could be divided into two groups of empirical and rational indices (Haghshenas et al., 2021). The former is derived from environmental variables and subjective estimates. One example is the correlation between subjective thermal sensation votes and measured microclimate parameters determined through multiple regression analysis. The rational indices are based on the heat balance equation of the human body. Common indicators for outdoor thermal comfort research are Predicted Mean Vote (PMV) (Fanger, 1970), Standard Effective Temperature (SET*) (Gagge et al., 1986), Outdoor Standard Effective Temperature (OUT_SET*) (Pickup and de Dear, 1999), Physiologically Equivalent Temperature (PET) (Höppe, 1999), and Universal Thermal Climate Index (UTCI) (Jendritzky et al., 2012). PMV, a heat balance model initially proposed by Fanger (1970), is more widely used for indoor conditions. SET* was developed by Gagge et al. (1986) based on Gagge's two-node model. PET based on the Munich energy-balance human body model–MEMI was introduced by Höppe (1999). To cover wider range of outdoor weather conditions, the UTCI index was designed based on Fiala's multi-node model (Jendritzky et al., 2012).

The existing standards and guidelines have no recommendations on which thermal comfort index is suitable for describing outdoor thermal comfort (Johansson et al., 2014; Fang et al., 2021; Haghshenas et al., 2021; Potchter et al., 2022). The choice of thermal index for outdoor thermal comfort evaluation has become a special research topic. In the Mediterranean climate, Tseliou et al. (2010) examined the ability of three indices, Discomfort index (DI), Cooling Power (CP), and PET, to describe the thermal sensation, illustrating that the performance of the three indices was limited. In an arid climate, Ruiz et al. (2015) demonstrated that there was a high contrast between subjective thermal sensation votes and the prediction results by six indices, including Temperature-Humidity Index (THI), Vinje's Comfort Index (PE), Thermal Sensation (TS), PMV, PET, and COMFA outdoor thermal comfort models, indicating that all models' testability was very low (below 25%). Pantavou et al. (2013) assessed the performance of numerous thermal indices to quantify the thermal sensation in Athens, Greece, demonstrating that the majority of the studied indices predicted approximately 35% of the thermal sensation votes. In severe cold area of China, Chen et al. (2020) compared the predictive ability of PET, SET*, and UTCI, demonstrated none of them applicable in predicting thermal perceptions. In cold region of China, Lai et al. (2014a) compared three different thermal comfort indices, PMV, PET, and UTCI, with the actual thermal reaction, proved that the UTCI provided a satisfactory outdoor thermal comfort prediction, while PMV overestimated it. In the hot-summer and cold-winter region of China, Wei et al. (2022) illustrated UTCI is better than PET for outdoor thermal comfort assessment. In Hong Kong, Ng and Cheng (2012) identified that PMV generally overestimated the thermal perception toward the warmer threshold in summer and *vice versa* in winter, recommended the use of PET as an alternative thermal index.

Residents in different regions have various thermal requirements due to climate adaptation (Lin, 2009). Furthermore, both psychological and physiological differences between ethnicities could influence human thermal perception (Lin, 2009). In addition, none of the mentioned thermal comfort models were built based on Chinese experimental studies. Furthermore, the yearly increase in the duration of hot weather in the humid subtropical areas of China (He et al., 2022; Yang et al., 2022) has a great impact on the use of outdoor space (Huang et al., 2022). Therefore, it is necessary to propose an adaptive model to quantify the correlations between urban microclimate and outdoor thermal sensation in humid subtropical residential areas of China and assess the effects of different design ideas on people's comfort. Therefore, the performances of different thermal indices for predicting thermal sensation in humid subtropical residential areas of China were evaluated.

2 Material and methods

2.1 Field surveys

2.1.1 Sites

The database of this study was conducted in Guangzhou, China. It has a humid subtropical climate under the Köppen climate classification. The monthly mean air temperature varied slightly throughout the year, with a range of 13–29°C (Figure 1), indicating a hot summer and a warm winter. The monthly mean relative humidity was higher, being more than 60% all year.

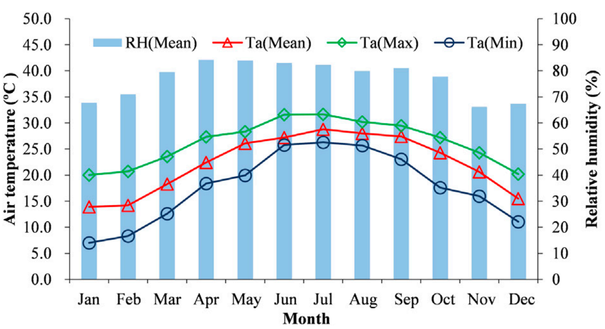

FIGURE 1
Monthly mean/maximum/minimum air temperature and mean relative humidity of Guangzhou based on the meteorological data from China Meteorological Administration and Tsinghua University (2005).

In order to obtain residents' thermal sensation votes under different urban microclimates, field survey sites were selected to capture a wide range of thermal environment level in humid subtropical residential areas of China. Wind environment, direct solar radiation, reflected solar radiation and long wave radiation were considered comprehensively. Finally, eight sites were selected. The site features are shown in Figure 2. There were different microclimate conditions in the eight survey sites (e.g., shaded, sunlit, windy, windless, *etc.*). Thus, the observational data covered a wide range of thermal environment that people may encounter in humid subtropical residential areas of China.

2.1.2 Questionnaire surveys

To obtain subjects' thermal comfort conditions in all possible weather conditions appeared in the hot and humid area of China, the questionnaire survey was designed from the cold season to the hot season. Table 1 summarized the questionnaire surveys schedule on 24 days. The questionnaire surveys were performed during the timeframes of 8:00–12:00 and 14:00–18:00 in cold season and shoulder season, and 7:00–12:00 and 15:00–19:00 in hot season, when the outdoor space was commonly used. Each activity site was visited once a day in each season. Two spots were not surveyed in shoulder season because of continuous rainy

FIGURE 2
Sites configurations. Sites A1, B3, and B4 are shaded and windless; Site C5 is shaded and windy; Sites A2 and D7 are sunlit and windy; Sites C6 and D8 are sunlit and windless.

TABLE 1 Surveys schedule.

Seasons	Month	Day	Questionnaires
Cold season	January	10, 17, 19, 22, 25, 28	305
	February	2, 8	
Shoulder season	April	4, 14, 16, 22, 23, 27	216
Hot season	June	20, 22, 27, 28	484
	August	2, 6, 19, 22	
	September	6, 11	

days, and two sites were surveyed twice in hot season. 1,005 valid questionnaires were obtained in this study: 305 in cold season, 216 in shoulder season, and 484 in hot season. The samples had a good balance of sex ratio (45.3% male and 54.7% female). The age of the survey subjects varied from 8 to 64 years old (mean age of 33.2 years old).

The questionnaire contained two parts. The first part was the subjects' personal information covered age, gender, height, weight, clothing worn, activity level, and reasons for visiting a particular place. The second section involved thermal perception related voting contained thermal sensation votes (TSV), thermal comfort votes (TCV), thermal acceptance vote and preference vote. The TSV in this study adopted the 9-point scale (i.e., "very cold" −4; "cold" −3; "cool" −2; "slightly cool" −1; "neutral" 0; "slightly warm" +1; "warm" +2; "hot" +3; "very hot" +4). The TCV was rated on a 4-point scale (i.e., "comfortable" 0; "slightly uncomfortable" +1; "uncomfortable" +2; "very uncomfortable" +3). The conventional 4-point scale (i.e., "clearly acceptable" +1; "just acceptable" +0.01; "just unacceptable" -0.01; "clearly unacceptable" -1) was used for thermal acceptability. The preference vote involved air temperature, relative humid, wind speed, and global radiation and was given on a 3-point scale (i.e., "decrease" −1; "not change" 0; "increase" +1).

2.1.3 Physical measurement

During the questionnaire survey, microclimatic variables (i.e., air temperature (Ta); relative humidity (RH); wind speed (V_a); globe temperature (Tg) and global radiation (G)) next to the interviewees were measured. Based on the recommended sensor height for standing subjects in ISO 7726 (ISO 7726, 1998), all instruments were placed at a height of 1.1 m above the ground. The accuracies of Ta sensor (HOBO Pro V2 U23-001), RH sensor (HOBO Pro V2 U23-001), V_a sensor (HD32.3), Tg sensor (HD32.3) and G sensor (LP 471 PYRA 02.5) were ± 0.20°C, ± 2.5%, ± 0.15 m/s, ± 0.50°C and ± 5 W/m^2, respectively. The ranges and accuracies of the instruments were all in accord with the ISO 7726 standard (ISO 7726, 1998). The Ta and RH sensors were shielded from solar irradiance with forced ventilation. On the measurement day, the thermal environment parameters were acquired at 1 min intervals.

2.2 Selected thermal indices and indices processing

In 2020, Li and Liu (2020) published a literature review article of 123 studies that investigated outdoor thermal comfort in China. The proportions of thermal indices applied in the reviewed publications are shown in Figure 3. The types of indices varied significantly among the studies. The most commonly used index was PET, followed by UTCI and SET*. In some outdoor thermal comfort studies of humid subtropical areas in China, local empirical thermal comfort index (TSV_{model}) have been developed through multiple linear regressions between actual thermal sensation votes and some microclimatic variables (Table 2). Therefore, the present study selected PET, SET*, UTCI, and TSV_{model} as the comparison indices.

Table 3 shows the selected thermal indices sorted by name and key parameters and the formulas or models for their calculation in the present study. The UTCI was calculated using "UTCI calculator" provided on the www.utci.org website (Bröde et al., 2012). PET was calculated using the RayMan software (Matzarakis et al., 2007). SET* was calculated using MATLAB code. All the thermal indices were calculated using the measured parameters 3-min average, as this was the estimated time for completing a questionnaire. The empirical thermal comfort index based on the annual data was selected as the TSV_{model}. The annual TSV_{model} in Guangzhou (Fang et al., 2021) was based on the voting of young college students. Therefore, the selected TSV_{models} was the empirical formula of Hong Kong (Cheng et al., 2012) located in the same climate zone as Guangzhou. The TSV_{model} (with RH) considered four microclimate variables, including air temperature, relative humidity, wind speed, and solar radiation, while the TSV_{model} (without RH) considered three microclimate variables, air temperature, wind speed, and solar radiation. The following equation was used to correct the wind speed at 10 m height.

$$V_m = V_a \times \left(\frac{H_m}{H_a}\right)^{0.22}$$

Where: V_m is the wind speed at the desired height (m/s), V_a is the measured wind speed (m/s), H_m is the desired height (m), and H_a is the measurement height 1.1 m.

The mean radiant temperature (T_{mrt}) is one of the most important variables for calculating PET, SET*, and UTCI. T_{mrt} is calculated from the measured globe temperature combined with measurements of wind speed and air temperature according to the following formula (Thorsson et al., 2007):

$$T_{mrt} = \left[\left(T_g + 273.15\right)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} (Tg\text{-}Ta)\right]^{0.25} - 273.15$$

where V_a is the measured wind speed (m/s), Ta is the air temperature (°C), Tg is the globe temperature (°C), D is the globe diameter (m), and ε is the globe emissivity.

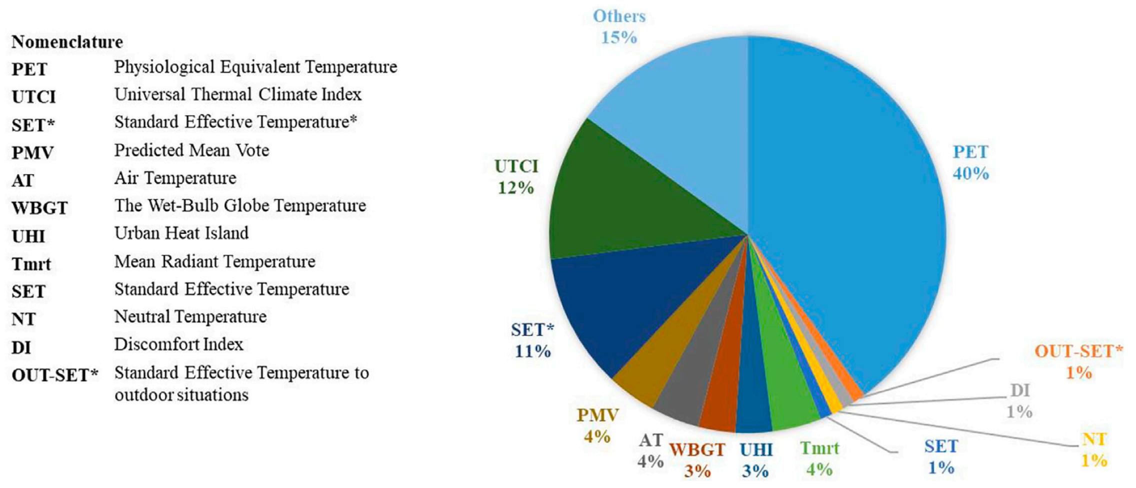

FIGURE 3
Frequency of thermal comfort indices application in outdoor thermal comfort studies of China. *Data from (Li and Liu, 2020)

TABLE 2 Thermal comfort regression models in humid subtropical areas of China.

References	Location	Empirical TSVmodel	R^2
Cheng et al. (2012)	Hong Kong, China	TSV_{model} (with RH) = 0.1185Ta − 0.6091V_a + 0.0025G + 0.1155RH − 4.77 (annual), TSV_{model} (without RH) = 0.1185Ta − 0.6091V_a + 0.0025G − 2.47 (annual)	0.91 0.90
Yang et al. (2013)	Changsha, China	TSV_{model} = 0.313Ta + 0.030T_{mrt} − 0.304V_a + 0.026RH − 11.622 (summer)	0.552
Lai et al. (2014b)	Wuhan, China	TSV_{model} = 0.0643Ta + 0.00076SR − 0.161V_a − 0.00376RH − 1.382 (summer and autumn)	0.670
Zhao et al. (2016)	Guangzhou, China	TSV_{model} = 0.245Ta + 0.059T_{mrt} − 0.457V_a + 0.013RH − 8.527 (summer)	0.598
Fang et al. (2021)	Guangzhou, China	TSV_{model} = 0.197Ta + 0.002RH − 0.373V_a + 0.014T_{mrt} + 0.161Clo + 0.141M − 4.741 (annual)	0.56

TABLE 3 Thermal indices along with the key parameters and the formulas or the models for their calculation.

Indices	Parameters	Formulas/models	References
PET	Ta, RH, V_a, T_{mrt}, M^a, Clo^a, Sex, Weight, Height	MEMI.model	Höppe (1999); Matzarakis et al. (2007)
SET^a	Ta, RH, V_a, T_{mrt}, M, Clo, Adu^a, Weight	Gagge's two-node model	Gagge et al. (1986)
UTCI	Ta, RH, $V_{10m}{}^a$, T_{mrt}	6th order polynomial calculated by Ta, RH, $V_{10m}{}^a$, T_{mrt}	Jendritzky et al. (2012); Bröde et al. (2012)
TSV_{model}	Ta, RH, V_a, G	TSV_{model} (with RH) = 0.1185Ta – 0.6091V_a + 0.0025G + 0.1155RH – 4.77 (R^2 = 0.91), TSV_{model} (without RH) = 0.1185Ta − 0.6091V_a + 0.0025G − 2.47 (R^2 = 0.90)	Cheng et al. (2012)

[a]Note: M is the metabolic rates; Clo is the clothing insulation; Adu is the surface area of the unclothed body; V_{10m} is the wind speed at a height of 10 m above the ground.

2.3 Data analysis

2.3.1 Three statistical and two qualitative criteria

Three statistical and two qualitative criteria were selected and established to verify the performance of thermal indices for quantifying outdoor thermal sensations (Monteiro and Alucci, 2006): 1) the coefficient of determination between the thermal comfort indices' parameters and TSV, 2) the Spearman's rho correlation coefficient between the thermal comfort indices value and TSV, 3) the percentage of correct

TABLE 4 Assessment scales of selected thermal indices.

Thermal sensation	PET (°C)	SET* (°C)	UTCI (°C)	TSV_{model}
Hot +3	>42	>44	>34	>2.5
Warm +2	36–42	38–44	28–34	1.5–2.5
Slightly warm +1	30–36	32–38	22–28	0.5–1.5
Neutral 0	24–30	26–32	16–22	−0.5–0.5
Slightly cool -1	18–24	20–26	10–16	−1.5~ −0.5
Cool -2	12–18	14–20	4–10	−2.5~ −1.5
Cold -3	<12	<14	<4	<−2.5

predictions, 4) the percentage of thermal comfort indices' class predictions, and 5) the distribution of thermal comfort indices' class predictions per class of TSV, assessed by cross-tabulation analysis.

The first coefficient of determination illustrated the possible potential of the model, indicating how well the model variables vary in function with variations in thermal responses. The second correlation verified the sensibility of the indices, showing how well the results of thermal comfort indices vary in function to variations in thermal responses. It has been argued that the coefficient of determination and Spearman's rho correlation coefficient are often inappropriate or misleading when comparing model-predicted and observed variables (Potchter et al., 2022). The relationship between the coefficient of determination and Spearman's rho correlation coefficient and model performance was not always consistent. Therefore, other evaluation criteria must be introduced. The last three criteria were selected to indicate the performance of the indices, focusing on the compare of coincidence between the prediction by the selected thermal indices and the actual thermal sensation votes perceived by the interviewees.

2.3.2 Thermal comfort indices' assessment scales

To apply the last three criteria, assessment scales for thermal comfort indices should be established. Table 4 lists the assessment scales of the selected thermal comfort indices. The assessment scales were established on the basis of earlier comfort researches: reasonable estimate threshold on thermal perception and the neutral temperature of previous studies in humid subtropical areas of China (de Dear and Brager, 1998; Lin and Matzarakis, 2008; Lin et al., 2011; Huang et al., 2016). The neutral PET was 27.17°C (Lin and Matzarakis, 2008), suggesting the neutral range was from 27.17 − 3.00 to 27.17 + 3.00, or simply 24–30°C. Correspondingly, the range of feeling "slightly warm" +1 was obtained through a 6°C increase of the range of "neutral" 0; and "slightly cool" −1 was obtained through a 6°C decrease of the "neutral" 0 range. The neutral SET* values were 28°C and 29.3°C in the cool and hot seasons, respectively (Lin et al., 2011). The SET* assessment scales were calculated based on neutral SET* 29°C. The assessment scales of the UTCI were calculated based on the neutral UTCI 19°C (Huang et al., 2016). Finally, the TSV_{model}'s assessment scales were set by the values ± 0.5, ±1.5, and ±2.5.

The analysis was further performed using *IBM SPSS* software. All variables presented in the following paragraphs were statistically significant at a confidence level equal to or less than 0.05 (Sig. ≤ 0.05).

3 Results and discussion

3.1 Microclimate conditions

The minimum, maximum, means, and standard deviations of the measured variables (including Ta, RH, V_a, and T_{mrt}) as well as the calculated thermal indices PET, UTCI and SET* were summarized in Table 5. Ta ranged between 14.7 and 38.3°C, which indicates that Guangzhou was climatically characterized by a hot summer and a warm winter. The variations in RH and T_{mrt} were significant throughout the year, as indicated by their standard deviations, with 17.9% and 7.7, respectively. RH ranged between 15.7 and 99.4% with an average value of 62.6% indicating relatively high humidity during the surveys. The variation in V_a was also significant, ranging between 0.0 and 3.9 m/s.

3.2 Outdoor thermal sensation

In the present study, the 9-point scale (i.e., "very cold" −4; "cold" −3; "cool" −2; "slightly cool" −1; "neutral" 0; "slightly warm" +1; "warm" +2; "hot" +3; "very hot" +4) of ISO 10551 was used to record thermal sensations, especially extreme hot sensations in the hot season. However, in previous studies in humid subtropical areas of China, in which the assessment scales were established based on, thermal sensation was rated on the ASHRAE 7-point scale (i.e., "cold"−3; "cool"−2; "slightly cool"−1; "neutral" 0; "slightly warm" +1; "warm" +2; "hot"

TABLE 5 The statistical results of the microclimate parameters.

Seasons		Ta (°C)	RH (%)	V_a (m/s)	T_{mrt} (°C)	PET (°C)	UTCI (°C)	SET* (°C)
Cold season	Min.	14.7	15.7	0.1	11.6	13.1	10.2	20.4
	Max.	26.4	89.7	3.9	37.1	28.8	27.4	32.6
	Mean	19.5	49.6	0.8	23.9	19.7	19.7	27.2
	St.Dev.	1.7	20.7	0.7	7.1	2.9	2.7	2.3
Shoulder season	Min.	22.8	56.5	0.0	22.3	26.6	28.2	28.6
	Max.	32.6	87.3	2.0	41.6	41.2	36.8	37.4
	Mean	25.7	70.3	0.7	26.9	30.9	31.1	31.9
	St.Dev.	1.6	7.4	0.4	3.1	2.3	1.6	1.6
Hot season	Min.	26.2	23.8	0.0	25.2	25.5	27.7	28.6
	Max.	38.3	99.4	3.2	68.5	55.3	47.4	43.6
	Mean	31.7	66.4	0.7	34.8	33.3	34.6	33.7
	St.Dev.	2.6	15.8	0.6	6.3	4.3	3.2	2.4
Annual	Min.	14.7	15.7	0.0	11.5	13.1	10.2	20.4
	Max.	38.3	99.4	3.9	68.5	55.3	47.4	43.6
	Mean	27.9	62.6	0.7	30.1	29.0	29.7	31.5
	St.Dev.	5.7	17.9	0.6	7.7	6.8	6.9	3.5

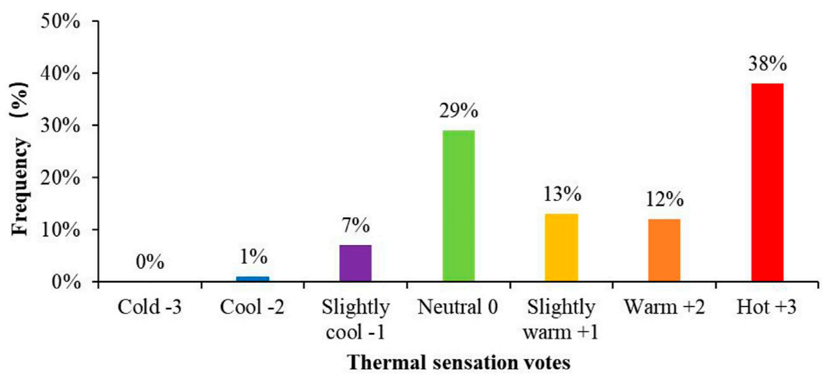

FIGURE 4
Frequency distributions of thermal sensation votes.

+3). To apply the last three criteria, comparing the prediction by the selected thermal indices with the actual thermal sensation indicated by the interviewees, the extreme categories such as "very hot" +4 and "very cold" −4 which rarely occurred with 4.1% and 0% respectively were merged to the categories of "hot" +3 and "cold" −3, respectively.

Figure 4 shows the frequency distribution of thermal sensation votes. The TSV ranged from "cool" −2 to "hot" +3. The highest frequencies of votes were "neutral" 0 and "hot" +3, with 29% and 38%, respectively. The "slightly warm" +1 and "warm" +2 votes were essentially the same, with 13% and 12%, respectively. While, the "slightly cool" −1 and "cool" −2 votes had few occurrences, for a total of 8%.

3.3 Comparison between selected indices' prediction and thermal sensation votes

3.3.1 Coefficient of determination and Spearman's rho correlation coefficient

The first two statistical criteria, the coefficient of determination between the thermal comfort indices' parameters and TSV and the Spearman's rho correlation coefficient between the results of the thermal comfort indices and TSV, were estimated, as shown in Table 6. The coefficients of determination were generally higher than Spearman's rho correlation coefficients. Moreover, strong associations were

TABLE 6 Coefficient of determination and Spearman's rho correlation coefficient.

Indices	Coefficients of determination	Spearman's rho correlation coefficient
TSV_{model} (with RH)	0.934	0.813
TSV_{model} (without RH)	0.942	0.833
PET	0.879	0.735
UTCI	0.880	0.761
SET*	0.752	0.665

found between coefficients of determination and Spearman's rho correlation coefficients, indicating that high coefficients of determination would predict high Spearman's rho correlation coefficients. This is because both coefficients have the same interpretation of prediction possibilities, and the coefficient of determination shows how well the model parameters vary in function to variations of thermal responses, while the Spearman's rho correlation coefficient verified how well the results of thermal comfort indices vary in function with variations in thermal responses.

TSV_{model} (with RH) and TSV_{model} (without RH) showed the highest coefficients, with coefficients of determination of 0.934 and 0.942 and Spearman's rho correlation coefficient of 0.813 and 0.833, respectively, followed by UTCI and PET, with 0.880 and 0.761, and 0.879 and 0.735, respectively; the lowest was observed in the case of SET* with 0.752 and 0.665.

3.3.2 Percentage of correct predictions and two qualitative criteria

According to the third criterion percentage of correct predictions, UTCI was the most successful index simulating 29.8% of thermal sensation votes (Table 7), followed by the TSV_{model} (with RH), TSV_{model} (without RH), and SET* simulating approximately 24.5%, while the lowest was observed in PET (16.5%).

The percentage of thermal index class predictions demonstrated significant differences compared with the original TSV, as shown in Figure 5. For all the selected thermal indices, discrepancies were mainly identified in the positive thermal sensation ("slightly warm" +1; "warm" +2; "hot" +3). The frequency of the original "hot" +3 was higher than the predictions of the selected thermal comfort indices, whereas the total frequencies of the original "slightly warm" +1 and "warm" +2 were lower than the predictions of the selected thermal comfort indices. Furthermore, PET overestimated the negative thermal sensation ("cool" −2 and "slightly cool" −1), while SET* overestimated the "neutral" 0. In contrast, UTCI showed better agreement with the primordial votes than the rest of the selected thermal comfort indices, indicating "hot" +3 and "neutral" 0 with 29% and 19%, respectively, compared with the original "hot" +3 with 38% and "neutral" 0 with 29%.

Cross-tabulation analysis was used to assess predictive ability of indices considering each class of TSV scale separately. Figure 6 shows the TSV cross-tabulation. The applicability of UTCI was also verified by cross-tabs. Approximately 57% of the UTCI's predictions were classified correctly as "hot" +3, while great success had also been observed in the case of class "neutral" 0 and "slightly cool" −1, at 40% and 48%, respectively. For the TSV_{model} (with RH), TSV_{model} (without RH) and PET, predictions were accurate only in the case of "hot" +3. All the SET*predictions were inaccurate.

3.3.3 Performance assessment

The average Spearman's rho correlation coefficient was evaluated as approximately 0.60, suggesting a moderate correlation (Willmott, 1982; Pantavou et al., 2013). For the selected thermal comfort indices, all indices correlated well with TSV, with coefficients greater than 0.60. In particular, the same better fits were found for TSV_{model} (with RH) and TSV_{model} (without RH), with coefficients larger than 0.80. Although all the selected thermal comfort indices had suitable applicability according to the first two statistical criteria, the last three criteria demonstrated limited performance; this proved that the coefficient of determination and the Spearman's rho correlation coefficient were often inappropriate or misleading when comparing model-predicted and observed variables (Willmott, 1982; Potchter et al., 2022). The relationships between the coefficient of determination and Spearman's rho correlation coefficient and model performance were not always consistent.

All the selected thermal indices had limited performance in the prediction of thermal sensation because the thermal sensation in the urban microclimate was a complex phenomenon with multiple factors of concern, the microclimate, physiological, psychological, and behaviors (Nikolopoulou et al., 2001; Nikolopoulou and Steemers, 2003; Chen and Ng, 2012). The microclimate in a certain region affects

TABLE 7 Percentage of indices' correct predictions.

Indices	TSV_{model} (with RH)	TSV_{model} (without RH)	PET	UTCI	SET*
Percentage of correct predictions	24.4%	24.3%	16.5%	29.8%	24.4%

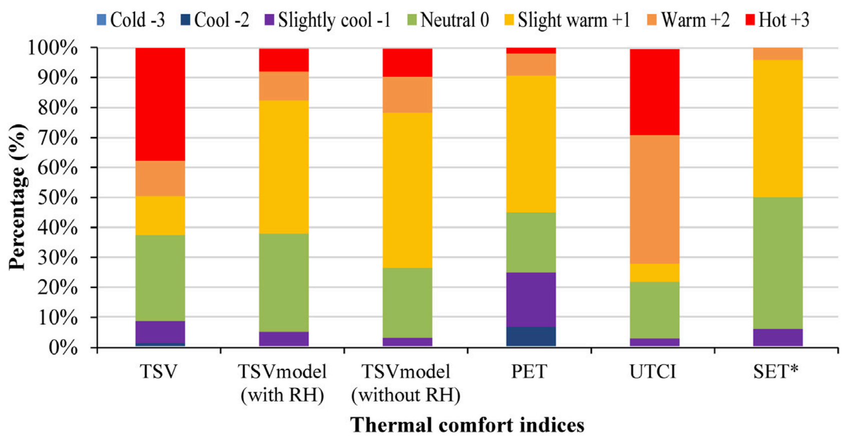

FIGURE 5
Percentage of thermal indices' class predictions.

	TSV	0%	1%	7%	29%	13%	12%	38%
TSV_{model} (with RH)		-3	-2	-1	0	1	2	3
0%	-3							
0%	-2							
5%	-1	4%	12%	**33%**	31%	6%	6%	8%
33%	0			8%	**36%**	17%	14%	25%
45%	1		1%	6%	30%	**10%**	10%	43%
10%	2			2%	13%	15%	**17%**	53%
8%	3			4%	11%	13%	9%	**63%**

	TSV	0%	1%	7%	29%	13%	12%	38%
SET*		-3	-2	-1	0	1	2	3
0%	-3							
0%	-2							
6%	-1	3%	5%	**36%**	31%	20%	2%	3%
44%	0		1%	8%	**36%**	14%	15%	26%
46%	1		1%	3%	21%	**12%**	10%	53%
4%	2		10%	7%	21%	14%	**10%**	38%
0%	3							

	TSV	0%	1%	7%	29%	13%	12%	38%
TSV_{model} (without RH)		-3	-2	-1	0	1	2	3
0%	-3							
0%	-2							
3%	-1	7%	17%	**32%**	27%	0%	7%	10%
23%	0			12%	**38%**	19%	13%	18%
52%	1		1%	5%	31%	**12%**	11%	40%
12%	2			5%	15%	11%	**18%**	51%
9%	3			3%	9%	15%	8%	**65%**

	TSV	0%	1%	7%	29%	13%	12%	38%
UTCI		-3	-2	-1	0	1	2	3
0%	-3							
0%	-2							
3%	-1	8%	12%	**48%**	16%	12%	0%	4%
19%	0		3%	14%	**40%**	21%	14%	8%
6%	1		3%	10%	18%	**13%**	28%	28%
43%	2			4%	34%	12%	**9%**	41%
29%	3		1%	4%	16%	10%	12%	**57%**

	TSV	0%	1%	7%	29%	13%	12%	38%
PET		-3	-2	-1	0	1	2	3
0%	-3							
7%	-2	3%	**9%**	24%	29%	28%	6%	1%
18%	-1		2%	**13%**	36%	35%	12%	2%
20%	0		1%	8%	**35%**	11%	15%	30%
46%	1		1%	4%	26%	**11%**	9%	49%
7%	2			3%	7%	15%	**10%**	65%
2%	3			6%	22%	17%	6%	**49%**

FIGURE 6
Distribution of thermal indices' class predictions per class of TSV (each row adds to 100%).

the thermal sensations directly (Chen and Ng, 2012), while psychological and behavioral factors play an important role in the determination of thermal evaluation of inhabitants (Brager and de Dear, 1998; Schweiker et al., 2013). The psychological and behaviors were not taken into consideration in the thermal comfort models of PET, UTCI, and SET*. In contrast, the TSV_{model} (with RH) and TSV_{model} (without RH) should have better performance because the equations were derived from the survey data implicit of the habits and customs of the residents. The limited performance of the TSV_{model} may be due to differences in habits and customs between Guangzhou and Hong Kong. In addition, the TSV_{models} were developed

TABLE 8 Quantitative measures of thermal indices' assessment scales performance with observed data.

Thermal indices	RMSE (°C)	RMSEs (°C)	RMSEu (°C)	*d*
TSV_{model} (with RH)	1.60	1.31	0.93	0.72
TSV_{model} (without RH)	1.54	1.23	0.93	0.77
PET	1.84	1.49	1.05	0.61
UTCI	1.43	1.09	1.08	0.84
SET*	1.68	1.56	0.82	0.59

based on the multiple linear regressions between the original thermal sensation votes and some local microclimatic parameters. Local microclimatic conditions play an important role in affecting thermal sensations of people (Chen and Ng, 2012). The varied microclimates under different topographic characteristics and urban morphologies led to various thermal sensations.

3.4 Adaptation analysis

The limited performance of the selected indices was examined using the last three criteria. The last three criteria were estimated based on the assessment scales of previous studies in the humid subtropical areas of China. The assessment scales may not have adapted to Guangzhou. A set of difference measures, including the root mean square error (RMSE), systematic error (RMSEs), unsystematic error (RMSEu), and an index of agreement (*d*), for model evaluation proposed by Willmott (1982) was used to quantitatively evaluate the adaptation of thermal comfort indices' assessment scales. The RMSE explains the extent of the average difference between the original and prediction. Both RMSEs and RMSEu derived from RMSE, explain how much of the RMSE is systematic in nature and what portion is unsystematic. As for a credible model, the magnitude of RMSEs should close to 0, while the result of RMSEu should approach RMSE. The index of agreement (*d*) is intended to be a descriptive measure of how a model predicts a variable with high accuracy. The *d* value of one represents a perfect prediction of the variable.

The difference measures are presented in Table 8. For UTCI, the RMSEs was relatively small, and the RMSEu approached the RMSE, indicating that the UTCI better conforms to the criteria of the systematic error. The *d* value for UTCI was 0.84, suggesting that the assessment scales of the UTCI reasonably approximated the observed data for this study. For all the other indices, the RMSEs were generally higher than the RMSEu, indicating that the assessment scales did not adapt in Guangzhou. The RMSEu was approximately one owing to the complexity of the outdoor thermal comfort evaluation.

4 Conclusion

The present study presented field survey results of outdoor thermal comfort, aiming to propose an adaptive model to quantify the correlations between urban climate and outdoor thermal sensations for humid subtropical residential areas in China. The paper presented the results of field thermal comfort survey focusing on the comparison between the prediction by thermal indices (i.e., PET, UTCI, SET* and TSV_{model}) commonly used in China and the actual thermal sensation expressed by interviewees. The main conclusions are as follows:

1. The TSV_{model} had a better correlation with TSV, while the UTCI was the most successful index, simulating 29.8% of TSV. The testability of PET and SET* were very low, with the correct predictive ability 16.5% and 24.4%, respectively.
2. For all the selected thermal comfort indices, the percentage of thermal comfort index class predictions demonstrated significant differences compared with the original TSV. In contrast, UTCI showed better agreement with the original, indicating 'hot' +3 and 'neutral' 0 with 29% and 19%, respectively, compared with the original +3 with 38% and 0 with 29%.
3. For all the indices, the RMSEs were generally higher than the RMSEu, demonstrating that the assessment scales did not adapt to Guangzhou. Therefore, it was necessary to establish the thermal sensation scales of Guangzhou. The RMSEu were approximately one owing to the complexity of the outdoor thermal comfort evaluation.
4. In the selected indices, the UTCI reasonably approximated the observed data for this study and was recommended to assess the outdoor thermal comfort in humid subtropical residentials of China to evaluate the thermal comfort level under different design decisions, thus creating a comfortable urban microclimate.

In our study, UTCI was calculated by 'UTCI calculator' provided on the www.utci.org website based on Ta, RH, V_{10m} and T_{mrt}. The 10 m high wind speed was required to calculate UTCI, as well as the mean radiant temperature (T_{mrt}) which was derived from RayMan software. The UTCI would be difficult to use in the actual design process in a more convenient way by designers and urban planners. However, we could propose some outdoor thermal comfort design strategies base on evaluation indexes UTCI. The proposed strategies would provide a common basis for the creating guidelines to use in future studies regarding creating a comfortable microclimate in the humid and subtropical residential area of China.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

KL: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, visualization, writing- original draft preparation, and writing-review and editing. XL: Conceptualization, methodology, visualization, software, writing- original draft preparation, writing-review and editing, and funding acquisition. YB: Conceptualization, resources, software, writing- original draft preparation, writing-review and editing, and funding acquisition.

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Conflict of interest

Authors XL and YB were employed by Architectural Design and Research Institute Co., Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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