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Assessment of outdoor thermal comfort in Hong Kong based on the individual desirability and acceptability of sun and wind conditions

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Abstract

Outdoor thermal comfort is crucial for encouraging people to participate in outdoor activities beneficial to human health. It can be achieved by employing appropriate urban design. An advanced assessment of outdoor thermal comfort can provide useful suggestions for urban design. Therefore, in this study, outdoor thermal comfort was assessed from a new perspective by investigating subjects' perceptions of sun and wind conditions. A field test including a physical measurement and a questionnaire survey was carried out. Subjects' thermal sensations and desirability of the sun and wind conditions were investigated using the Universal Thermal Climate Index (UTCI). The acceptability of sun or wind conditions to subjects were proposed to reveal the influences of sun and wind conditions on subjects. The results showed that the surveyed thermal sensation responding to the UTCI depended on the desirability of sun and wind conditions for subjects. The probability of these desirabilities fitted well with the UTCI in logistic regressions. The expected mean thermal sensation votes (MTSV) versus UTCI determined considering the effects of these desirabilities on thermal sensations was better agreed with the surveyed MTSV. Acceptable UTCI ranges of 16.5–35.0°C and 18.5–32.5°C were determined by sun acceptability and wind acceptability respectively. Wind conditions were predominant in influencing subjects' thermal perceptions at UTCI of less than 26.0°C, while sun conditions were predominant at UTCI of greater than 26.0°C. Subjects were more tolerant of sun conditions than wind conditions. These investigations are significant for thermally comfortable urban design and future studies.

Keywords: Outdoor thermal comfort; Universal thermal climate index (UTCI); Thermal sensation votes; Sun and wind desirability; Sun and wind acceptability

Nomenclature

OUT_SET* Standard Effective Temperature for Outdoor

UCB model UC-Berkeley thermal comfort model

UEB Underneath-elevated-building

UTCI Universal Thermal Climate Index

PET Physiological Equivalent Temperature

SVF Sky View Factor

H/W Ratio of height and width of building

I_{clo} Clothing insulation

M Metabolic rate, Met

T_a Air temperature, ℃

T_g Globe temperature, ℃

T_{mrt} Mean radiant temperature, ℃

v Wind speed

RH Relative humidity, %

v_{10} Wind speed at 10 m

K_i Short-wave irradiance, W/m^2

L_i Long-wave irradiance, W/m^2

α_k Absorption coefficients of the clothed human body in short-wave radiation

ε_p Emissivity of the clothed human body in long-wave radiation

σ Stefan-Boltzmann constant

W_i Angle factor between human and the ambient

TCV Thermal Comfort Vote

TSV Thermal Sensation Vote

D_S Sun desirability

D_W Wind desirability

P_{Ds} Probability of the sun desirability

P_{Dw} Probability of the wind desirability

P_{TCV} Probability of the thermal comfort vote

A_S Sun acceptability

A_W Wind acceptability

MTSV Mean Thermal Sensation Vote

$MTSV_{Ds}$ Expected mean thermal sensation vote in terms of the sun desirability

$MTSV_{Dw}$ Expected mean thermal sensation vote in terms of the wind desirability

1. Introduction

Physical or recreational outdoor activities are strongly encouraged owing to their benefits for citizens' health, positive emotions, and stress reduction. However, urban heat island effects caused by rapid urbanization have altered local climate environments and can affect outdoor activities [1]. Concerns about urban heat island effects and the increasing demands of citizens for outdoor recreational activities have brought increasing attention to the issue of outdoor thermal comfort in urban areas [2].Outdoor thermal comfort is an important factor in attracting people for outdoor activities, and it can be significantly affected by urban design [3-6]. Thus, outdoor thermal comfort studies are important for providing suggestions to urban designers in designing urban environments and citizens in participating in outdoor activities.

Over the years, studies on outdoor thermal comfort have been carried out in different climate regions and urban areas and have made significant contributions to explaining thermally comfortable outdoor environments [7-11]. Assessments of outdoor thermal comfort which aim to explore the effects of personal and meteorological factors on the perception of microclimate environments are significant in outdoor thermal comfort studies. Field studies combining on-site measurements of meteorological parameters and questionnaire surveys have been largely applied to assess outdoor thermal comfort at the precinct scale [2]. Some previous studies have applied thermo-physiological indices, such as the physiological equivalent temperature (PET) [12], universal thermal climate index (UTCI) [13], UC-Berkley thermoregulation model [14], or the standard effective temperature for outdoor (OUT_SET*) [15] to correlate with surveyed thermal sensations for predicting local thermal sensations. These indices address effects of four meteorological parameters (solar radiation, wind speed, ambient air temperature, and humidity) and two personal factors (metabolic rate and clothing insulation) on thermal perceptions of people based on human energy balance theory [16] and human thermoregulation model [17]. However, one outdoor thermal comfort study in Hong Kong demonstrated that the correlation between the PET and surveyed thermal sensations variated with different microclimate environments within one campus area [18]. Additionally, these correlations depend on the season; subjects feel hotter in summer than in winter at the same PET value due to the thermal adaptation [19]. Lin et al. found that in Taiwan, the thermal comfort characteristics indicated by the correlation between PET and thermal sensation in hot and humid climate regions differed from those in temperate climate regions [20]. Similar results were obtained by Lam et al, Huang et al, and Lai et al in applying UTCI to assess outdoor thermal comfort [10, 18, 21]. It is assumed that human thermal sensation is not only influenced by the physical and physiological effects of addressed six parameters evaluated by thermo-physiological indices, but also by other factors related to human psychology such as thermal history, culture, adaptation, and acclimation [22]. Or people are more sensitive to the change of those parameter, which could not be captured by thermal indices. [23]. A single thermal index is insufficient to represent actual human thermal sensations.

In outdoor thermal comfort studies, evaluation of the relative influence of meteorological parameters on outdoor thermal comfort is also significant. It can help urban designers to modify a predominant parameter by building morphology and green infrastructure to effectively improve outdoor thermal comfort [5, 6, 24-26]. Yang et al [27], Walton et al [28], and Xie et al [23] verified that the wind speed and solar radiation in microclimate environments were the dominant factors influencing human thermal perceptions. Some studies have found that the shading effect provided by buildings with certain height/width (H/W) ratios and trees with high sky view factor (SVF) is significant for reducing solar radiation and improving outdoor thermal comfort in summer [5, 29]. Others have concluded that lifted buildings with the first floor built on stilts are efficient for amplifying wind speed and improving outdoor thermal comfort on hot days [30, 31]. Useful suggestions for urban designers to determine when, where and whether to improve sun or wind conditions for improving outdoor thermal comfort are required. Although the overall effect of microclimate environments on people can be obtained from a thermo-physiological index, the relative influence of sun and wind conditions corresponding to a thermo-physiological index on people is not clear. Therefore, aforementioned suggestions cannot be provided with a given value of a thermo-physiological index. Additionally, although acceptable microclimate environments can be determined by various methods [32, 33], those determined by acceptable sun or wind conditions which are practical for urban designers and can be achieved by urban interventions have not been discussed.

To address the aforementioned challenges, this study aimed to assess outdoor thermal comfort by investigating individual perceptions of sun and wind conditions, including sun and wind desirability and sun and wind acceptability, in complex microclimate environments. On the one hand, previous studies have seldom specifically addressed individuals' perceptions of sun and wind conditions in terms of desirability and acceptability [34, 35]. Sun or wind desirability reflecting individuals' desire of changing or maintaining sun or wind conditions for thermal comfort is a subjective evaluation related to both physiological and psychological factors that may influence the thermal sensation. On the other hand, assessing sun and wind acceptability can compare the effects of sun and wind conditions on the thermal comfort and help to determine acceptable microclimate environments for people. Therefore, sun and wind desirability are investigated and evaluated with corresponding thermal sensations against a thermo-physiological index UTCI. Acceptability of sun and wind conditions, which is derived from the desirability of sun and wind conditions and the overall thermal comfort, are also investigated at varying UTCI. This study assesses outdoor thermal comfort from a new perspective by examining the relationship between thermal sensation and UTCI with perceptions of sun and wind conditions and intuitively revealing the influence of sun and wind conditions perceived by subjects. The results of this study will provide useful information for urban designers to improve outdoor thermal comfort and suggest further outdoor thermal comfort study directions.

2. Methodology

2.1 Study area

This study was carried out on a university campus in Hong Kong based on a field study consisted of on-site measurements of meteorological parameters and questionnaire surveys. The various microclimate environments caused by specific building morphologies and green infrastructure elements make this university campus a suitable area to conduct an outdoor thermal comfort study. Three typical sites in the campus were selected as the study area, as shown in Figure. 1. Sites 1 and 3 are called UEB sites, located in the spaces beneath elevated buildings, which are typical building morphologies on this campus. Site 2 is called OPEN site, an open square where the solar radiation is strong for most of the day.

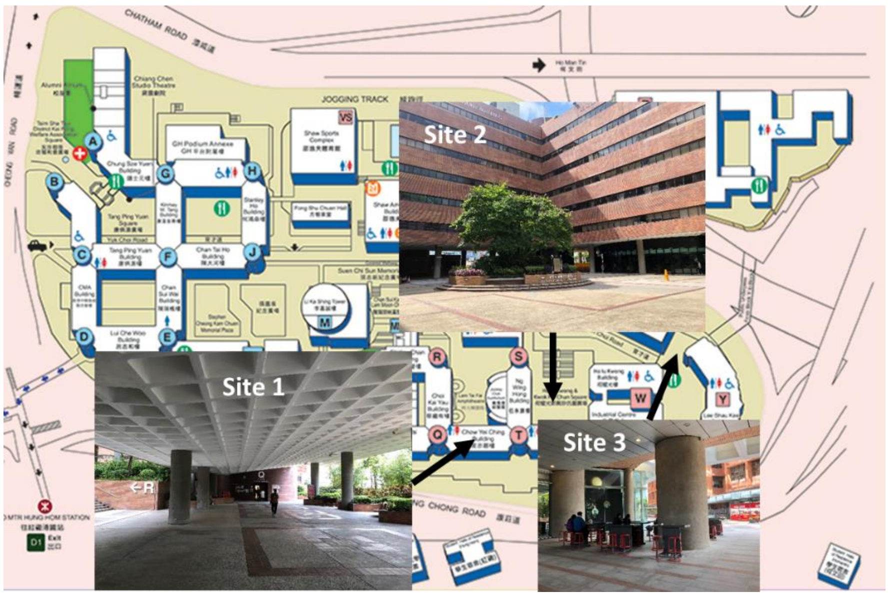


Fig. 1 Selected sites for the field survey

2.2 Field survey

The field survey was conducted during the early afternoon on 23 days between March 2016 and December 2016. Different weather types corresponding to summer, autumn, and winter in Hong Kong were covered in this study [18]. On each survey day, subjects were required to wear suitable clothing according to the forecast outdoor air temperature and experience the microclimate environments at each of the three sites in turn. The subjects were required to spend 15 min participating in mild activities (sitting, standing, or wandering) as they want at each site, some of them sitting and others standing or wandering for the whole 15 min. They were also required to record the time they spent on sitting, standing or wandering during this 15 min. Due to each activity type corresponding to a certain metabolic rate, the weighted-average metabolic rate of one subject conducting required activities was then determined in this 15 min to represent the average activity level. It is to help subjects to adapt to the microclimate environments and approach thermal steady state at each site before filling out the questionnaire. The ethical approval was obtained from the institution before conducting these field surveys. ~~The subjects spent 15 min participating in mild activities (sitting, standing, and wandering) at each site to adapt to the microclimate environment before filling out the questionnaire.~~

2.2.1 On-site meteorological measurements

Meteorological measurements were conducted using a movable mini weather station to record meteorological parameters, including the air temperature (T_a, °C), wind speed (v, m/s), irradiance including short-wave irradiance and long-wave irradiance (Q_s/Q_l, W/m^2), relative humidity (RH, %), and black globe temperature (T_g, °C) at 1.5 m above the ground. The movable mini weather station and instruments for measuring meteorological parameters are shown in Fig. 2. The short-wave and long-wave irradiance from six directions (north–south, east–west, and up–down) were measured using 3 sets of net radiometers (CNR4, KIPP&ZONEN) with high sensitivity. The instruments for measuring T_g, v, T_a, ~~and~~ RH, and irradiance ~~have been detailed in a previous study~~is listed in Table 1 [18]. All of the instruments used are recommended by the ASHRAE handbook for meteorological parameter measurements [36].

Table 1 Specifications of measurement instruments

Meteorological parameter	Instrument	Measuring Range	Accuracy
Air temperature (T_a)	R.M.YOUNG 41382	-50-50 (°C)	±0.3°C
Relative humidity (RH)		0-100 (%)	±1%
Wind speed (V_a)	R.M.YOUNG 81000	0-40 (m/s)	±0.05m/s
Globe temperature (T_g)	TJHY HQZY-1	-40-60 (°C)	±0.3°C
Long-wave irradiance (Q_l)	Kipp & Zonen CNR-4	-250-250 (W)	<10%
Short-wave irradiance (Q_s)		0-2000 (W)	<5%

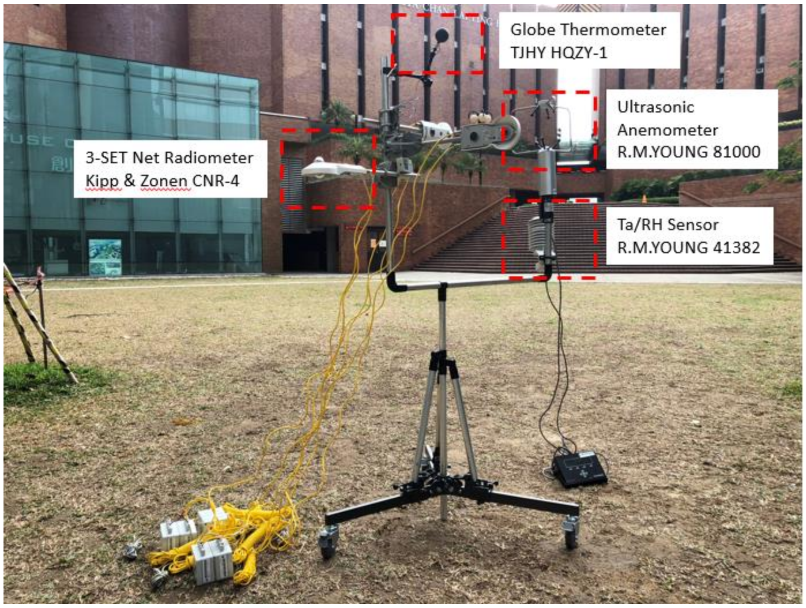


Fig. 2 Mini weather station with instruments for measuring meteorological parameters

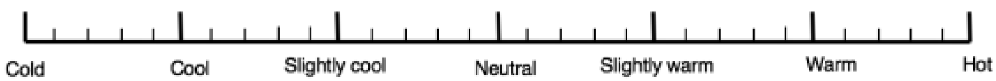
2.2.2 Questionnaire survey

Subjects for the questionnaire survey were recruited from the university, and a total of 1107 questionnaires were collected. The questionnaire was divided into two parts: questions in the first part involved personal perceptions of the microclimate environments, including the thermal sensation vote (TSV), overall thermal comfort vote (TCV), and evaluation of the sun and wind conditions; questions in the second part involved personal information, including age, gender, height, weight, clothing status, and activity level during the prior 15 min.

According to the questionnaire results, the average metabolic rate indicating the activity level of the subjects was 1.18 Met with a standard deviation of 0.23 Met. Because that 87.3% of metabolic rates concentrated in a range of 1.0-1.3 Met, and the number of data of different metabolic rate was very limited, an average metabolic rate of 1.18 Met was adopted to represent the outdoor activity level of subjects in this study. The average clothing insulation of the subjects was 0.36 ~~I_{clo}~~ clo during the summer field tests and 0.59 ~~I_{clo}~~ clo during the winter field tests. Subjects in this study were all Chinese adults with the age from 20 to 50 (young and middle-aged) and lived in Hong Kong for more than a year. The average age of all subjects was 25. Among these subjects, 523 of them were male and 589 of them were female. The average weight of the female was 52.17kg and that of the male was 67.33kg. The average heights of the female and male were 161.2cm and 172.9cm, respectively. Questions related to thermal sensation (ASHRAE seven-point scale), thermal comfort (five-point scale), and the evaluation of sun and wind conditions were discussed and analyzed in this study. These questions are listed in Table 2.

Table 2 Questions 1–4 of the questionnaire

1. What do you want to improve for sunlight?				
Less sunlight (1)	No change needed (2)	More sunlight (3)		
2. What do you want to improve for wind?				
Less wind (1)	No change needed (2)	More wind (3)		
3. Dressed as you are at the moment, please tick the scale to show how you currently feel.				



4. How would you describe the whole thermal environment?				
Very uncomfortable (-2)	Uncomfortable (-1)	Neutral (0)	Comfortable (1)	Very comfortable (2)

In Table 2, the "sunlight" in Question 1 may include both the light and heat effects of the sun, and the "wind" in Question 2 may include convective cooling and other effects of the wind. Therefore, the answers to Questions 1 and 2 reflect the desire of subjects to change or maintain sun and wind conditions are kind of psychological responses influenced by physiological and psychological status of subjects. The sun desirability (D_S) and wind desirability (D_W) were measured using a three-point scale of subjective feedback: too strong (less sunlight desired, $D_S = 1$), just right (no change in sunlight desired, $D_S = 2$), or too weak (more sunlight desired, $D_S = 3$). Likewise for the wind desirability: too strong (less wind desired, $D_W = 1$), just right (no change in wind desired, $D_W = 2$), and too weak (more wind desired, $D_W = 3$).

2.3 Data analysis

2.3.1 Index for assessing outdoor thermal comfort

Thermal perceptions of subjects are investigated in complex microclimate environments. The universal thermal climate index (UTCI), which is a thermo-physiological index, is used in this study to estimate the effects of aforementioned six parameters on people by an equivalent air temperature [37]. Based on this estimation, further assessment of outdoor thermal comfort is carried out and can be more easily understood.

The UTCI was developed based on the most advanced "Fiala" multi-node thermal regulation model, and is used to describe the thermal stress imparted on the human body by a thermal environment [38]. It is defined as the air temperature of a reference environment which can produce the same thermal stress as an actual environment, and is composed of the air temperature (T_a, °C), mean radiant temperature (T_{mrt}, °C), wind speed at 10 m over the floor (v_{10}, m/s), and relative humidity (*RH*, %). Owing to the advanced clothing model [39] coupled with the UTCI model, and the assumption of a constant metabolic rate of 2.3 Met of people in the UTCI model ~~and the assumption of a metabolic rate of less than 1.4 Met of people in the UTCI model~~ [13], UTCI is only a function of four meteorological parameters: T_a, T_{mrt}, v_{10}, and *RH* (Eq. 1). Thus, UTCI is a suitable simple and user-friendly index to roughly estimate the effects of microclimate environments on people with low metabolic rates. The UTCI was calculated using the BioKlima 2.6 software package [40].

$$\text{UTCI} = \text{f}(T_a; T_{mrt}; v_{10}; RH) = T_a + Offset(T_a; T_{mrt}; v_{10}; RH) \quad (1)$$

2.3.2 Calculation of mean radiant temperature and wind speed at 10 m above the ground

The mean radiant temperature (T_{mrt}) is an input for calculation of the UTCI, and is an important parameter in outdoor thermal comfort studies. T_{mrt} can be calculated based on the globe temperature or the six-directional short-wave and long-wave irradiance. Owing to its accuracy, the latter six-directional technique was used in this study to obtain the T_{mrt} in the outdoor environment [41]. T_{mrt} can be calculated with Eq. (2) using collected short-wave and long-wave irradiance data.

$$T_{mrt} = \sqrt[4]{\sum_{i=1}^{6} \frac{W_i\left(\alpha_k K_i + \varepsilon_p L_i\right)}{\varepsilon_p \sigma}} - 273.1 \quad (2)$$

A detailed explanation of this equation was provided in a previous study conducted by Huang et al [18].

For calculation of the UTCI, the wind speed at 10 m above the ground is required rather than the wind speed measured at the pedestrian level. Therefore, the wind speed measured at 1.5 m above the ground needs to be converted to a wind speed at 10 m above ground using Eq. (3) [42].

$$v_{10} = v \times \frac{\log(\frac{10}{0.01})}{\log(\frac{x}{0.01})} \quad (3)$$

where v_{10} is the wind speed at 10 m above ground, v is the measured wind speed, and x is the height of the mini weather station, which has a value of 1.5 m.

2.3.3 Logistic regression of the sun desirability (D_S) and wind desirability (D_w)

The desire of subjects to change or maintain the sun and wind conditions, D_S and D_W, are important parts of thermal perception. Because D_S and D_W are psychological factors which might be influenced by individual physiological and psychological status, the probability of D_S and D_W versus UTCI was investigated to explore the relationship between desirability and thermal stress of microclimate environments on people estimated by UTCI. The probability of subjects' D_S and D_W values as a function of UTCI was obtained through a logistic regression analysis [43].

As introduced in Section 2.2.2, there are three options for D_S and D_W: $D_S = 1$, $D_S = 2$, and $D_S = 3$; and $D_W = 1$, $D_W = 2$, and $D_W = 3$. First, the options $D_S = 1$ or $D_W = 1$ are coded as 1, while the other options are all coded as 0. For example, the options of desiring to decrease the wind or sun conditions for subjects are coded as 1, while all the others (with no desire to decrease them) are coded as 0. Then, the probability of $D_S = 1$ or $D_W = 1$ ($P_{Ds=1}$ or $P_{Dw=1}$) is determined for each UTCI bin with a width of 1 °C, and is associated with the UTCI by a logistic regression, as expressed in Eq. (4) and Eq. (7). Next, the options $D_S = 3$ or $D_W = 3$ are coded as 1, while the other options are all coded as 0. Similarly, the probability of $D_S = 3$ or $D_W = 3$ ($P_{Ds=3}$ or $P_{Dw=3}$) against UTCI bins can be obtained through logistic regression, as expressed in Eq. (5) and Eq. (8). As the sum of probabilities of $D_S = i, (i = 1,2,3)$ or $D_W = i, (i = 1,2,3)$ must be 100%, the probability of $D_S = 2$ or $D_W = 2$ ($P_{Ds=2}$ or $P_{Dw=2}$) can be easily determined as expressed in Eq. (6) and Eq. (9).

$$P_{Ds=1} = \frac{1}{1+e^{-Z_{Ds=1}}} \tag{4}$$

$$P_{Ds=3} = \frac{1}{1+e^{-Z_{Ds=3}}} \tag{5}$$

$$P_{Ds=2} = 1 - \frac{1}{1+e^{-Z_{Ds=1}}} - \frac{1}{1+e^{-Z_{Ds=3}}} \tag{6}$$

$$P_{Dw=1} = \frac{1}{1+e^{-Z_{Dw=1}}} \tag{7}$$

$$P_{Dw=3} = \frac{1}{1+e^{-Z_{Dw=3}}} \tag{8}$$

$$P_{Dw=2} = 1 - \frac{1}{1+e^{-Z_{Dw=1}}} - \frac{1}{1+e^{-Z_{Dw=3}}} \quad (9)$$

where $P_{Ds=i(i=1,2,3)}$ and $P_{Dw=i(i=1,2,3)}$ are the probabilities of $D_S = 1$, $D_S = 2$, and $D_S = 3$ and $D_W = 1$, $D_W = 2$,and $D_W = 3$ against UTCI, and vary between 0 and 1; and $Z_{Dw=i\ (i=1,3)}$ and $Z_{Dw=i\ (i=1,3)}$ are functions of the UTCI, as shown in Eqs. (10) and (11).

$$Z_{Ds=i\ (i=1,3)} = b_i UTCI + b_{i0} \quad (10)$$

$$Z_{Dw=i\ (i=1,3)} = c_i UTCI + c_{i0} \quad (11)$$

where b_i and c_i are coefficients, and b_{i0} and c_{i0} are intercepts which can be obtained through a regression analysis.

2.3.4 Derivation of the sun acceptability (A_S) and wind acceptability (A_W)

Questionnaire results are grouped by D_S or D_W values. In each group with a D_S or D_W value of 1, 2, or 3, the percentage of surveyed TCVs representing neutral (0), comfortable (1), and very comfortable (2) conditions is determined. If this percentage is greater than 80%, the corresponding microclimate environment is labeled as acceptable for a group with a certain D_S or D_W value. The effects of the sun or wind conditions in these microclimate environments on the subjects in this group are also defined as acceptable, regardless of whether these subjects wanted to change or maintain the sun or wind conditions, and the acceptability of the sun and wind conditions, denoted as $A_{S,i\ (i=1,2,3)}$ and $A_{W,i\ (i=1,2,3)}$, respectively, are assigned a value of 1. For example, in a group where the subjects all selected $D_S = 2$, if the percentage of TCVs of 0, 1, and 2 in this group is greater than 80%, then $A_{S,2}$ is equal to 1. The conception of 80% in this study is illustrated by thermal comfort studies of Fanger et al [44].

If the aforementioned percentage is lower than 80% for a group with a certain D_S or D_w value, the corresponding microclimate environments for subjects in this group are said to be unacceptable, and the corresponding wind and sun conditions are recognized as factors contributing to these unacceptable microclimate environments. Thus, $A_{S,i\ (i=1,2,3)}$ or $A_{W,i\ (i=1,2,3)}$ is assigned a value of -1. In this way, the actual effects of sun or wind conditions on subjects voting for $D_S = i, (i = 1,2,3)$ or $D_W = i, (i = 1,2,3)$ can be labeled with $A_{S,i\ (i=1,2,3)}$ or $A_{W,i\ (i=1,2,3)}$ values of 1 or -1, as expressed by the following equations:

$$A_{S,i\ (i=1,2,3)} = \begin{cases} 1 & \left(P_{TCV=0,1,2} \middle| D_S = i, (i = 1,2,3)\right) \geq 80\% \\ -1 & \left(P_{TCV=0,1,2} \middle| D_S = i, (i = 1,2,3)\right) < 80\% \end{cases} \tag{12}$$

$$A_{W,i\ (i=1,2,3)} = \begin{cases} 1 & \left(P_{TCV=0,1,2} \middle| D_W = i, (i = 1,2,3)\right) \geq 80\% \\ -1 & \left(P_{TCV=0,1,2} \middle| D_W = i, (i = 1,2,3)\right) < 80\% \end{cases} \tag{13}$$

where $P_{TCV=0,1,2}$ is the percentage of surveyed TCVs that are neutral (0), comfortable (1), and very comfortable (2); and $\left(P_{TCV=0,1,2} \middle| D_S = i, (i = 1,2,3)\right)$ or $\left(P_{TCV=0,1,2} \middle| D_W = i, (i = 1,2,3)\right)$ represents that $P_{TCV=0,1,2}$ is determined for each data set grouped by D_S and D_W values of 1, 2, or 3.

As introduced in Section 2.3.3, there is a probability distribution of D_S or D_W versus UTCI. The overall sun or wind acceptability (A_S or A_W) can then be determined against the UTCI using the probability-weighted average value of $A_{S,i\ (i=1,2,3)}$ or $A_{W,i\ (i=1,2,3)}$ for each UTCI, as given in Eq. (14) and Eq. (15).

$$A_S = \sum_{i=1}^{3}\left(P_{Ds=i} \times A_{S,i}\right) \tag{14}$$

$$A_W = \sum_{i=1}^{3}\left(P_{Dw=i} \times A_{W,i}\right) \tag{15}$$

where $P_{Ds=i}$ and $P_{Dw=i}$ are the probabilities of D_S and D_w, respectively. The outputs of A_S and A_W are between -1 and 1, and indicate the degree of sun and wind acceptability perceived by subjects, respectively, under thermal stress of microclimate environments estimated by the UTCI. For UTCI values where A_S or A_W are greater than 0, the effects of the corresponding wind or sun conditions on subjects are acceptable. The higher the A_S or A_W values are, the greater the degree of acceptability. For UTCI values where A_S or A_W are less than 0, the effects of the corresponding sun or wind conditions are said to be unacceptable.

2.3.5 ANOVA analysis

ANOVA analysis (An analysis of variance) [45] was conducted in this study to test the differentiation of surveyed thermal sensations of subjects voting for different sun or wind desirability under a specific UTCI range in a statistical way. The differentiation is verified by statistical significance which is referred to as the P-value, the probability of obtaining a result of a study at least as extreme, given that the null hypothesis was true. The P-value of lower than a set significance level α (probability of the study rejecting the null hypothesis, given that it was true) indicates that the result of ANOVA test rejects the null hypothesis and is statistically significant [46]. The significance level is typically set to 5% in scientific researches [47]. Therefore, if $P<0.05$ is obtained from the ANOVA analysis in this study, the significantly different thermal sensations of subjects voting for different sun and wind desirability would be confirmed.

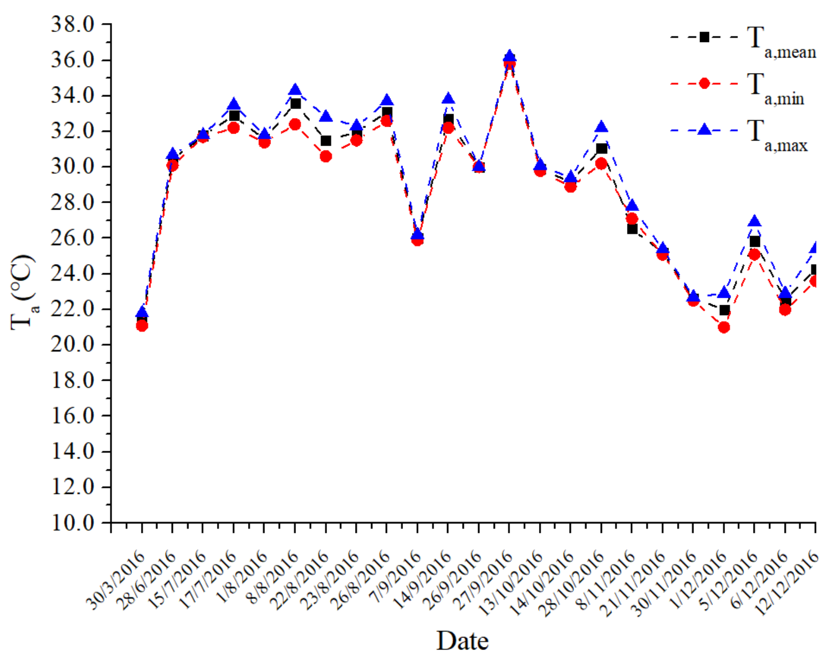
3. Results and Discussion

3.1 Meteorological parameters

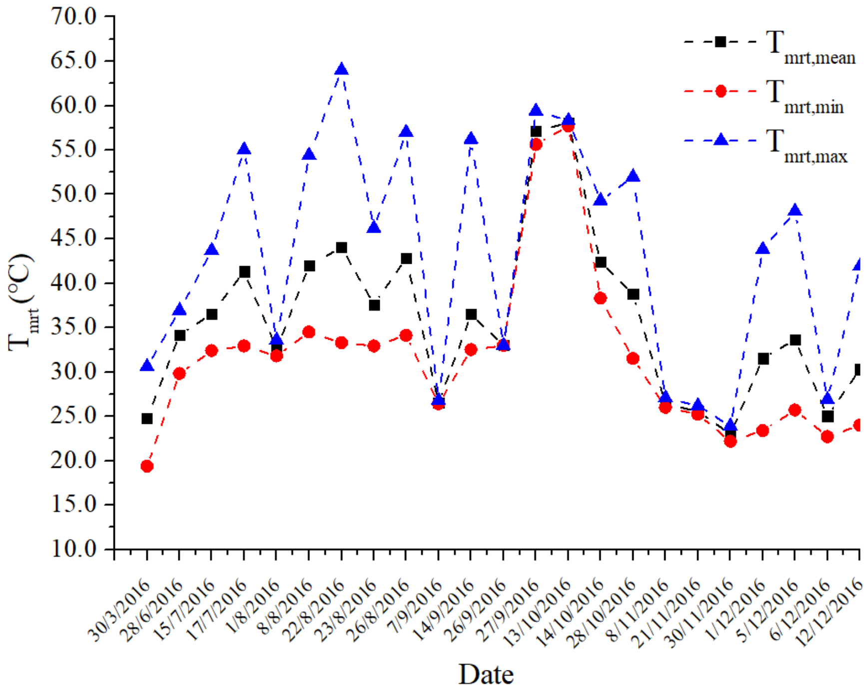
Figure 3 shows the meteorological parameters T_{mrt} (℃), Ta (℃), v (m/s), and RH (%) collected during field tests conducted on 23 days between March and December 2016. During the 6 field tests conducted on Oct. 13, Nov. 11, Dec. 1, Sep. 7, Sep. 26, and Sep. 27, 2016, meteorological parameters were collected only at the OPEN or UEB site from either 13:00–14:00 or 15:00–16:00. On the remaining measurement days, meteorological parameters were collected at UEB and OPEN in turn during 13:00–14:00 or 15:00–16:00. Figure 3 shows the maximum, minimum, and mean values of each meteorological parameter recorded during the field tests. Figure 3a shows that T_a varies between 21.1℃ and 36.2℃ and Figure 3b shows T_{mrt} from 19.4℃ to 59.4℃. The maximum value of the short-wave irradiance and the corresponding direction for each measurement day are listed in Table 3, indicating sunny or cloudy conditions on that day. A large difference between the minimum and maximum values of T_{mrt} is observed for measurement days on which the irradiance was collected at the UEB and OPEN sites in turn. This is due to different irradiance recorded at the UEB sites with shading and the OPEN site exposed directly to the sun for the same sunny/cloudy conditions. Figure 3c shows the wind speed recorded during the field test periods. Large deviations in the wind speed from 0.5 m/s to 3.5 m/s are observed for the measurement days, and the mean wind speed is within the range of 1.0–2.0 m/s. Figure 3d shows the variation in the relative humidity. Similar to T_a in Figure. 3a, small deviations in RH are observed on measurement days. Except for on Sep. 27 and Dec. 6, 2016, the RH was greater than 50%, demonstrating the humid climate of Hong Kong. Because field tests were conducted at different sites over different seasons, the parameters collected in the various microclimate environments are helpful for a comprehensive understanding of the microclimate environments.

Table. 3 Maximum values of the short-wave irradiance, the observed direction, and corresponding sunny/cloudy conditions

Date	Direction	Short-wave irradiance (W/m^2)	Sunny/cloudy condition
6/28/2016	Up	217.5	Partly cloudy
7/15/2016	Up	222.6	Partly cloudy
7/17/2016	Up	30.5	Cloudy
8/01/2016	Up	63.6	Cloudy
8/08/2016	Up	620.9	Clear and Sunny
8/22/2016	Up	890.9	Clear and Sunny
8/23/2016	Up	352.6	Partly cloudy
8/24/2016	Up	742.5	Clear and Sunny
9/14/2016	Up	720.4	Clear and Sunny
10/14/2016	Up	402.9	Partly cloudy
10/28/2016	Up	295.6	Partly cloudy
11/21/2016	Up	18.6	Cloudy
11/30/2016	Up	16.1	Cloudy
12/05/2016	Up	283.6	Partly cloudy
12/06/2016	Up	24.5	Cloudy
12/12/2016	Up	335.1	Partly cloudy

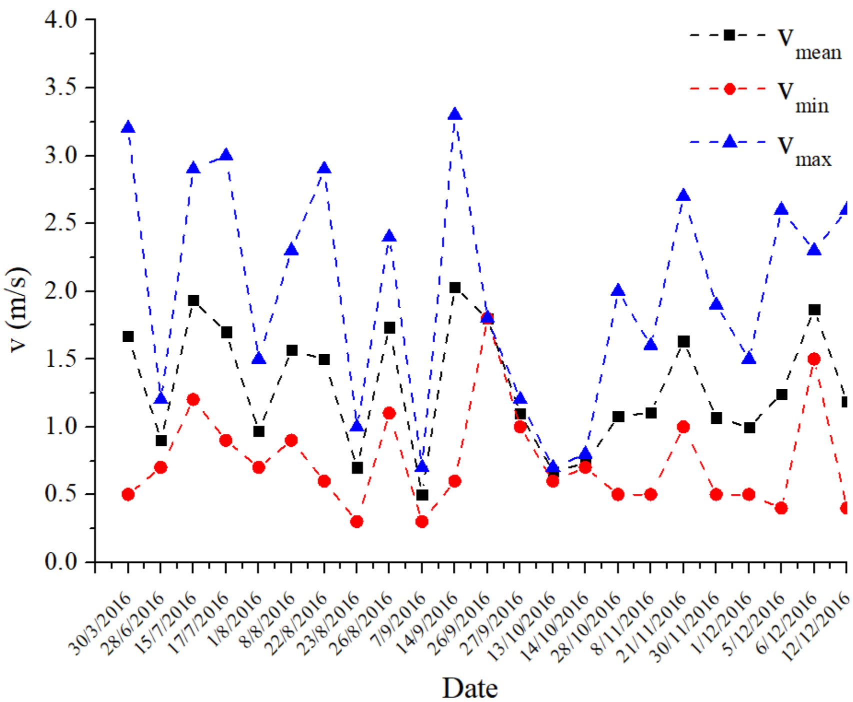


a)



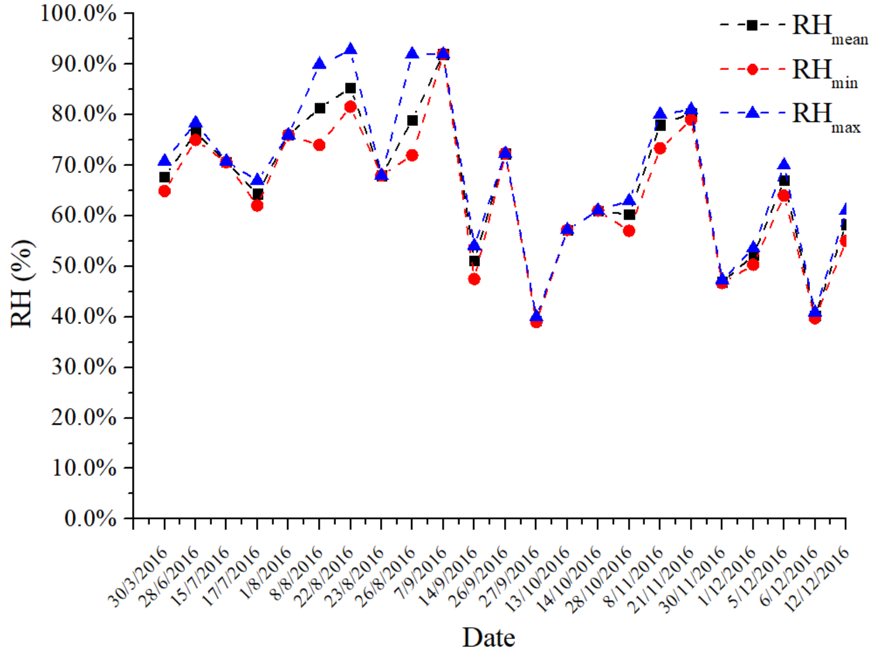
$T_{mrt,mean}$
$T_{mrt,min}$
$T_{mrt,max}$
T_{mrt} (°C)
Date

b)



v_{mean}
v_{min}
v_{max}
v (m/s)
Date

c)



d)

Fig. 3. Maximum, minimum, and mean values of the meteorological parameters measured during field test periods: a) air temperature, b) mean radiant temperature, c) wind speed, and d) relative humidity

3.2 Relationship among the thermal sensation vote, sun or wind desirability (D_S or D_w), and UTCI

A preliminary assessment of the outdoor thermal comfort at selected sites determined by the UTCI is shown in Figure. 4, which displays the correlation between the UTCI and the mean surveyed thermal sensation vote (MTSV) obtained for each UTCI value using a linear regression analysis. The relationship between the UTCI and the surveyed MTSV can be expressed by Eq. (16). However, the obvious deviation in the surveyed TSV for each UTCI value is shown with the error bars for each surveyed MTSV in Figure. 4, and the goodness of fit indicated by R^2 value for the regression line is not very high. It is not convincing to describe the surveyed TSV responding to the UTCI using the direct regression line alone. The data set in Figure. 4 was then divided into six sets according to the sun desirability of $D_S = 1$ (less sun desired), $D_S = 2$ (no change in sun desired), and $D_S = 3$ (more sun desired), and the wind desirability of $D_W = 1$(less wind desired),

$D_W = 2$ (no change in wind desired), and $D_W = 3$ (more wind desired), and the linear regression analysis between the surveyed MTSV and UTCI for each data set was carried out. The results were shown in Figures 4 and 5, and it is interesting to note that the surveyed MTSV at a given UTCI is affected by the sun and wind desirability of the subjects. By dividing the linear regression results in Figure. 4 into various sets according to reported sun desirabilities of $D_S = 1$ (less sun desired), $D_S = 2$ (no change in sun desired), and $D_S = 3$ (more sun desired), or wind desirabilities of $D_W = 1$(less wind desired), $D_W = 2$ (no change in wind desired), and $D_W = 3$ (more wind desired), it is interesting to note that the surveyed MTSV at a given UTCI depends on the sun and wind desirability of the subjects.

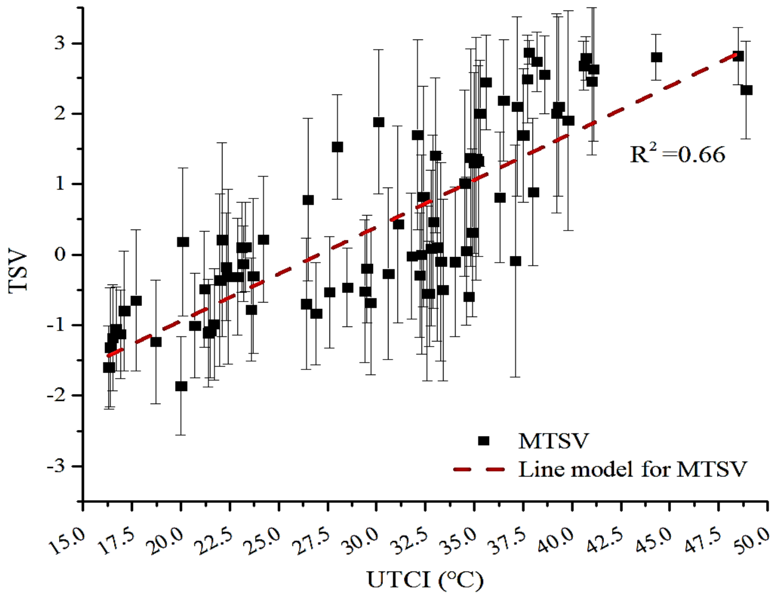
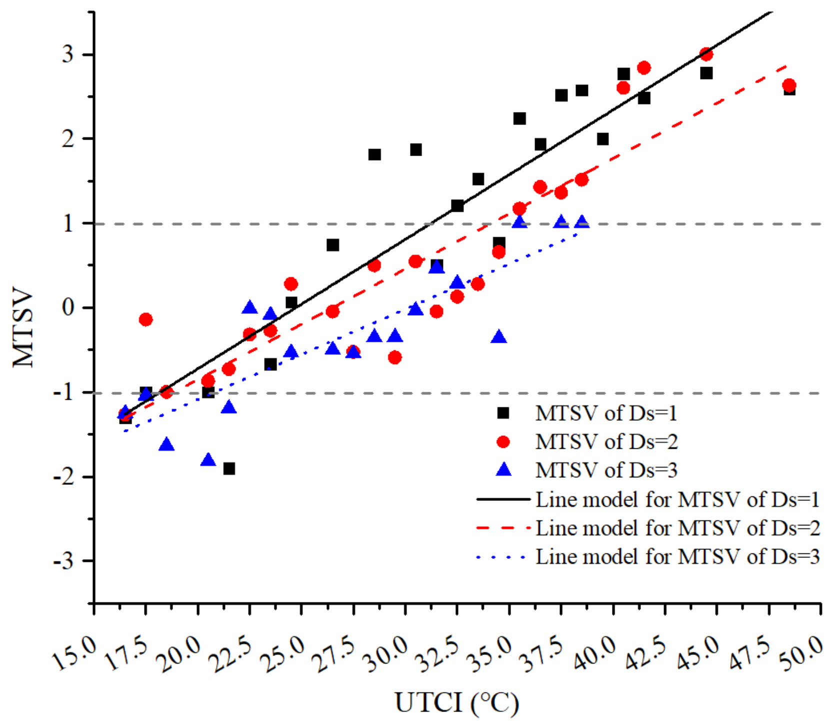
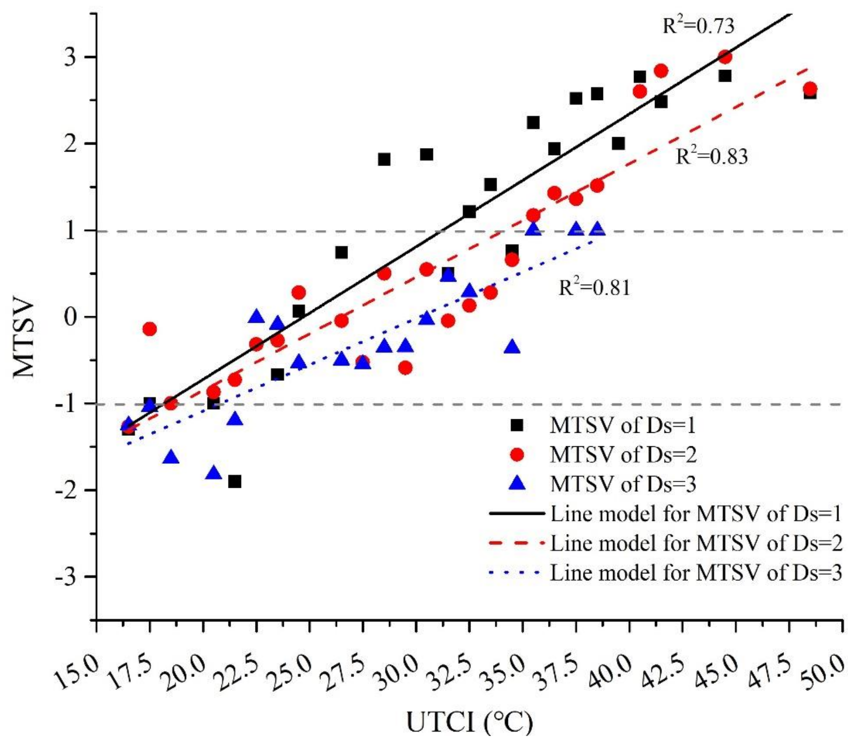


Fig. 4. Correlation between the surveyed TSV and the UTCI at all sites

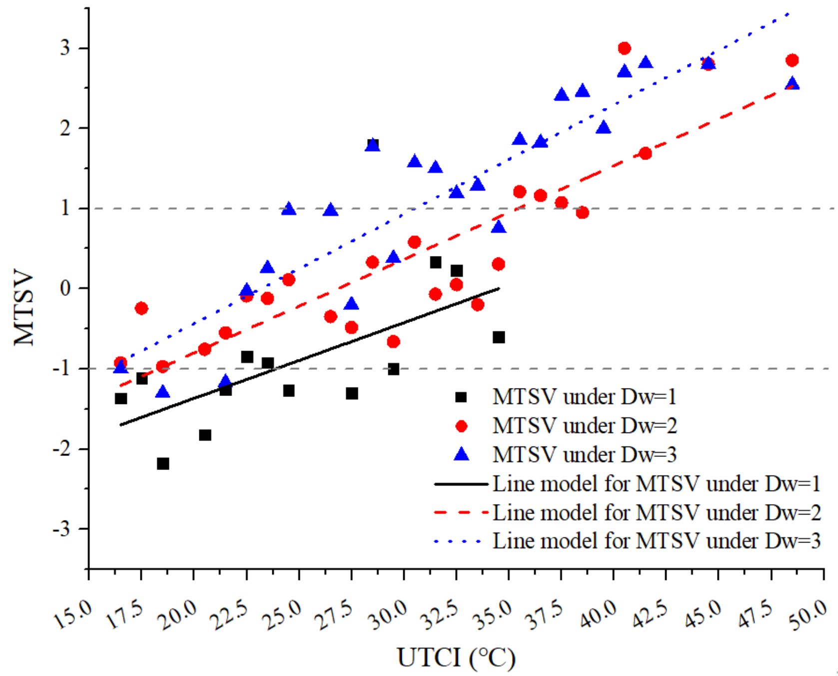


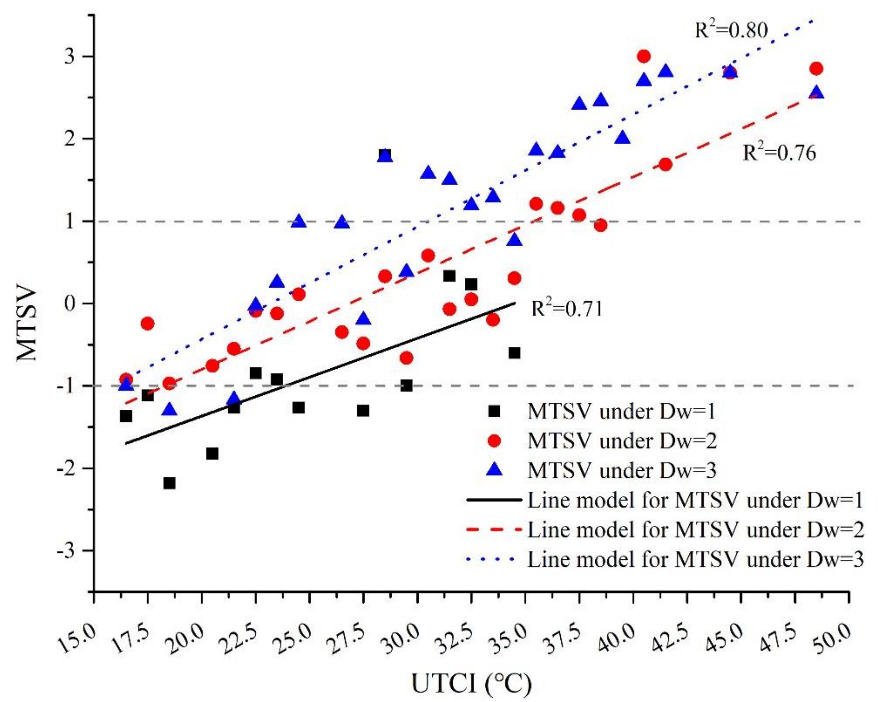
MTSV
UTCI (℃)
MTSV of Ds=1
MTSV of Ds=2
MTSV of Ds=3
Line model for MTSV of Ds=1
Line model for MTSV of Ds=2
Line model for MTSV of Ds=3



R²=0.73
R²=0.83
R²=0.81
MTSV
UTCI (℃)
MTSV of Ds=1
MTSV of Ds=2
MTSV of Ds=3
Line model for MTSV of Ds=1
Line model for MTSV of Ds=2
Line model for MTSV of Ds=3

a)





b)

Fig. 5. Surveyed MTSV vs. UTCI, grouped by a) sun desirability, b) wind desirability

Figure 5 shows the correlation between the surveyed MTSV for each UTCI bin and the UTCI bins are grouped by the sun desirability and the wind desirability, respectively. From Figure. 5a, three different regression lines with R^2 of greater 0.7 are obtained, and describe the correlation between the UTCI and the surveyed MTSV for subjects voting for $D_S = 1$, $D_S = 2$, and $D_S = 3$, as expressed in Eqs. (17)–(19), respectively. According to these regression lines, although the surveyed MTSV increases with increasing UTCI, the MTSV of subjects voting for $D_S = 1$ is higher than that of subjects voting for $D_S = 2$ and $D_S = 3$ at the same UTCI value. It is noted that the spacing between the lines, indicating a difference in the surveyed MTSV among subjects voting for $D_S = 1$, $D_S = 2$, and $D_S = 3$, increases with increasing UTCI. Subjects desiring less sun are more sensitive to the UTCI than subjects desiring others. After an ANOVA test which was briefly introduced in section 2.3.5 for the UTCI range of 16.5–38.5°C in which $D_S = 1$, $D_S = 2$, and $D_S = 3$ were all observed, differences were apparent in the surveyed MTSV among subjects voting for $D_S = 1$, $D_S = 2$, and $D_S = 3$, and was verified by P = ~~<~~0.05 (lower than 0.05).

The result is that subjects with different sun desirabilities are found in the same UTCI bin, leading to significantly different thermal sensations responding to this UTCI bin. The significance of the negative correlation between thermal sensation and sun desirability was tested with a Pearson correlation value of -0.544 with $P<0.05$. Various sun desirabilities in the same UTCI bin is perhaps caused by the psychological status of the subjects. For example, in sunny conditions, subjects who enjoy the sunshine in their daily life may desire more sun or no change in the sun and feel less hot than subjects who dislike sun exposure in their daily life and desire less sun. Another possible reason is the physiological status of the subjects. Various sun intensities may be estimated to have the same thermal stress on subjects by the UTCI value, but the body of subjects may be more sensitivity to effects of these various sun intensities, leading to different thermal stress felt by subjects than that represented by UTCI. Therefore, different sun desirability was appeared responding to different thermal stress. These assumptions should be verified by further studies.

$$\mathrm{MTSV} = 0.1332UTCI - 3.6039 \qquad (16.5°\mathrm{C} \leq \mathrm{UTCI} \leq 48.5°\mathrm{C},\ R^2 = 0.660) \tag{16}$$

$$MTSV_{Ds=1} = 0.1532UTCI - 3.7864 \quad (16.5°\mathrm{C} \leq \mathrm{UTCI} \leq 48.5°\mathrm{C},\ R^2 = 0.814) \tag{17}$$

$$MTSV_{Ds=2} = 0.1308UTCI - 3.4646 \quad (16.5°\mathrm{C} \leq \mathrm{UTCI} \leq 48.5°\mathrm{C},\ R^2 = 0.826) \tag{18}$$

$$MTSV_{Ds=3} = 0.1070UTCI - 3.2268 \quad (16.5°\mathrm{C} \leq \mathrm{UTCI} \leq 38.5°\mathrm{C},\ R^2 = 0.730) \tag{19}$$

Similarly, three different regression lines are obtained from Figure. 5b, and describe the correlation between the UTCI and surveyed MTSV for subjects voting for $D_W = 1$, $D_W = 2$, and $D_W = 3$, which are expressed by Eqs. (20)–(22), respectively. R^2 values of greater than 0.7 indicate a good correlation between the surveyed MTSV and UTCI for each group. The regression lines illustrate that subjects desiring more wind feel hotter than subjects desiring no change in wind or less wind. Compared to Figure. 5a, the spacing between the lines which indicates the difference in the surveyed MTSV among subjects voting for $D_W = 1$, $D_W = 2$, and $D_W = 3$ is clearly larger than those among subjects voting for $D_S = 1$, $D_S = 2$, and $D_S = 3$, and also increases with increasing UTCI. Subjects desiring more wind are more sensitive to the UTCI than subjects desiring others. The result is that thermal sensations of subjects responding to microclimate environments depend more on the wind desirability of subjects than the sun desirability. An ANOVA test indicating significant differences (P=0.001, lower than 0.05) An ANOVA test indicating significant differences (P<0.01) in the surveyed MTSV among subjects with different wind desirability was carried out for a UTCI range of 16.5–34.5℃ where options of $D_W = 1$, $D_W = 2$and $D_W = 3$ were all observed, and a UTCI range of 35.5–48.5℃, where the options $D_W = 2$ and $D_W = 3$ were observed.

It is also interesting to note that various wind desirabilities were found in the same UTCI bin, leading to deviations in the thermal sensations within that UTCI bin. The significance of the positive correlation between thermal sensation and wind desirability was tested with a Pearson correlation value of 0.610 with P<0.05. Similarly, there are two explanations for this phenomenon. One is the subjects' psychological attitude toward wind conditions. For example, under the same wind speed, subjects who prefer calm wind in daily life may desire less wind and feel cooler than subjects preferring strong wind who may desire more wind or no change in the wind. The other explanation may be the physiological status of subjects. There may be various wind speeds estimated as causing the same thermal stress to the subjects by the UTCI value, but the subjects are more sensitive to effects of these wind speeds on their body.

$$MTSV_{Dw=1} = 0.0944UTCI - 3.2556 \quad (16.5℃ \leq \text{UTCI} \leq 34.5℃,\ R^2 = 0.701) \tag{20}$$

$$MTSV_{Dw=2} = 0.1168UTCI - 3.1360 \quad (16.5℃ \leq \text{UTCI} \leq 48.5℃,\ R^2 = 0.757) \tag{21}$$

$$MTSV_{Dw=3} = 0.1365UTCI - 3.1615 \quad (16.5℃ \leq \text{UTCI} \leq 48.5℃,\ R^2 = 0.804) \tag{22}$$

Further, the acceptable UTCI range was determined through the intersections of the regression line, the slightly cool (-1) line, and the slightly warm (1) line. Acceptable UTCI ranges of 18.5–31.5℃ for subjects with $D_S = 1$, 19.5–33.5℃ for subjects with $D_S = 2$, and 20.5–38.5℃ for subjects with

$D_S = 3$ were obtained. Similarly, acceptable UTCI ranges of 16.5–30.5°C for subjects with $D_W = 1$, 18.5–35.0°C for subjects with $D_W = 2$, and 23.5–34.5°C for subjects with $D_W = 3$ were obtained. This confirms that subjects voting for $D_S = 1$ or $D_W = 3$ can only tolerate narrower UTCI ranges. In conclusion, irrespective of psychological factors or the stronger sensitivity of subjects to sun and wind conditions, the thermal sensation experienced by subjects at a given UTCI depends on their desirability of sun and wind conditions. Therefore, the sun and wind desirability versus UTCI needs to be investigated further.

3.3 Logistic regression analysis of the sun desirability (D_S) and wind desirability (D_w)

In the previous section, the importance of sun and wind desirability were emphasized, and this section will further discuss the subjects' desirability for sun and wind conditions in relation to the UTCI. After conducting the logistic regression analysis as introduced in Section 2.3.3, the probabilities of $D_S = i, (i = 1,3)$ and $D_W = i, (i = 1,3)$ ($P_{Ds=i(i=1,3)}$ and $P_{Dw=i(i=1,3)}$) versus UTCI are expressed as in Eqs. (23)–(26). Figure 6a shows the logistic regression analysis between $P_{Ds=i(i=1,3)}$ and UTCI, while Figure. 6b shows the logistic regression analysis between $P_{Dw=i(i=1,3)}$ and UTCI. The suitability of the logistic regression models for describing the probability of $D_S = i, (i = 1,3)$ and $D_W = i, (i = 1,3)$ versus UTCI was evaluated by R^2 and root mean square error (RMSE) which indicates the error between fitted data by regression model and observed data, and the results are listed in Table 4.

$$P_{Ds=1} = \frac{1}{1+e^{-(0.28 \cdot UTCI - 9.88)}} \tag{23}$$

$$P_{Ds=3} = \frac{1}{1+e^{-(2.99 - 0.16 \cdot UTCI)}} \tag{24}$$

$$P_{Dw=1} = \frac{1}{1+e^{-(5.18 - 0.28 \cdot UTCI)}} \tag{25}$$

$$P_{Dw=3} = \frac{1}{1+e^{-(0.25 \cdot UTCI - 8.28)}} \tag{26}$$

Table. 4 Values of R^2 and RMSE for fitness evaluation of the logistic models

Logistic model	R^2	RMSE
Logistic model for $P_{Ds=1}$	0.97	0.053
Logistic model for $P_{Ds=3}$	0.94	0.041

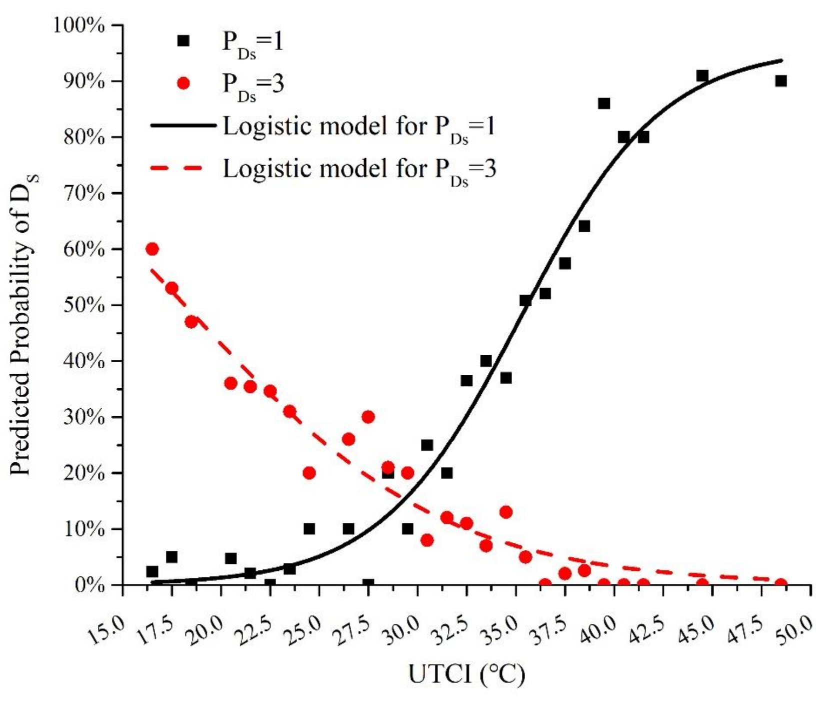
Logistic model for $P_{Dw=1}$	0.95	0.040
Logistic model for $P_{Dw=3}$	0.97	0.060

Because the sum of probabilities of $D_S = i, (i = 1,2,3)$ and $D_W = i, (i = 1,2,3)$ at each UTCI bin must equal 100%, the probabilities for $D_S = 2$ and $D_W = 2$ can be easily determined by the following equations:

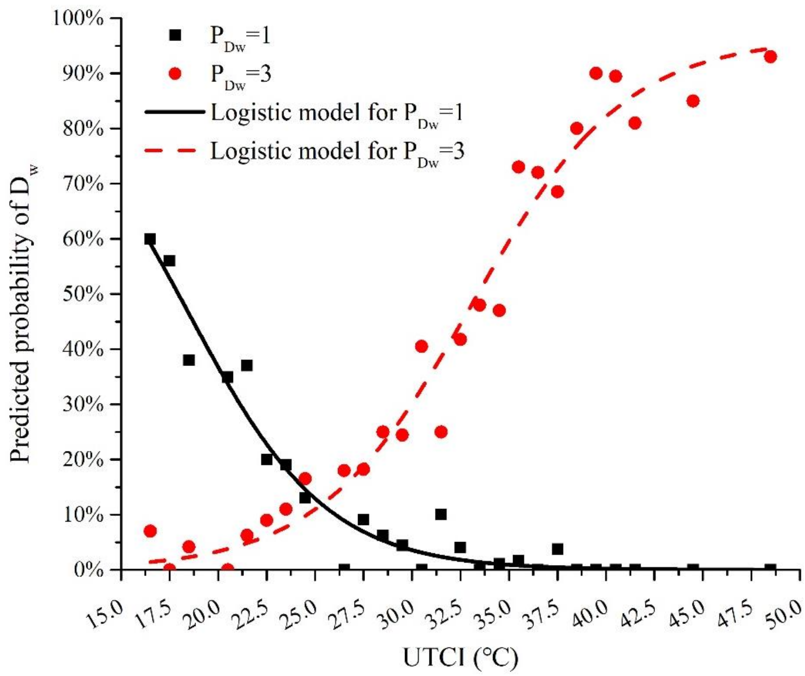
$$P_{Ds=2} = 1 - \left(\frac{1}{1+e^{-(0.28 \cdot UTCI - 9.88)}} + \frac{1}{1+e^{-(2.99 - 0.16 \cdot UTCI)}}\right) \tag{27}$$

$$P_{Dw=2} = 1 - \left(\frac{1}{1+e^{-(5.18 - 0.28 \cdot UTCI)}} + \frac{1}{1+e^{-(0.25 \cdot UTCI - 8.28)}}\right) \tag{28}$$

The R^2 values for the models of $P_{Ds=2}$ and $P_{Dw=2}$ are both 0.94, and the RMSE values for the two models are 0.056 and 0.059, respectively. Indicated by high values of R^2 and low values of RMSE, logistic regression models are very suitable for describing the probability of $D_S = i, (i = 1,2,3)$ and $D_W = i, (i = 1,2,3)$ versus UTCI.



a)



b)

Fig. 6. Logistic regression analyses between the probability of $D_S = i, (i = 1,3)$ or $D_W = i, (i = 1,3)$ and UTCI: a) probability of $D_S = i, (i = 1,3)$ versus UTCI; b) probability of $D_W = i, (i = 1,3)$ versus UTCI

Figure 6a shows that $P_{Ds=1}$ increases with increasing UTCI, while $P_{Ds=3}$ decreases with increasing UTCI. More than 80% of subjects desire less sun when the UTCI reaches 40.0°C, while more than 50% of subjects desire more sun when the UTCI is less than 17.5°C. The intersection point of 29.0°C in Figure. 6a indicates the point at which the sum of $P_{Ds=1}$and $P_{Ds=3}$ has reached its minimum value of 30%. In other words, the maximum value of $P_{Ds=2}$ of 70% is observed at this UTCI. Figure 6b shows that $P_{Dw=3}$ increases with increasing UTCI, while $P_{Dw=1}$ decreases with increasing UTCI. Similarly, at UTCI of greater than 40.0°C, more than 80% of subjects desire more wind, while at UTCI of less than 17.5°C, more than 50% desire less wind. Combining the results observed in Figure. 6a, it can be concluded that more than 80% of subjects desire a change in the wind and sun conditions at UTCI of greater than 40.0°C, while more than 50% of subjects desire changes in sun and wind conditions at UTCI of less than 17.5°C. However, the maximum $P_{Dw=2}$ of 78% is observed at the intersection point at 25.0℃ in Figure 6b, which is lower than that for the $P_{Ds=2}$ of 70% in Figure. 6a. Due to higher value of the UTCI indicating stronger heat stress estimated on subjects, it is interesting to note that microclimate environments where most of the subjects desire to maintain the sun conditions have stronger heat stress on subjects than those where most subjects desire to maintain the sun conditions.

3.4 Expected MTSV corresponding to UTCI

The correlation between the UTCI and surveyed MTSV of subjects voting for $D_S = i, (i = 1,2,3)$ and $D_W = i, (i = 1,2,3)$, and $P_{Ds=i(i=1,2,3)}$ and $P_{Dw=i(i=1,2,3)}$versus UTCI have been determined. The probability-weighted average value of $MTSV_{Ds=i\ (i=1,2,3)}$ or $MTSV_{Dw=i\ (i=1,2,3)}$ obtained from Eqs. (17)–(22) was then determined for each UTCI value using Eqs. (29) and (30) to develop an expected MTSV ($MTSV_{D_S}$ or $MTSV_{D_W}$) at each UTCI. This expected MTSV represents the most likely thermal sensation responding to UTCI after considering influences of D_S and D_W of subjects on thermal sensations and their distributions versus UTCI.

$$MTSV_{D_S} = \sum_{1=1}^{3} MTSV_{Ds=i} \times P_{Ds=i} = \frac{0.0224UTCI - 0.3218}{1 + e^{-(0.28 \cdot UTCI - 9.88)}} + \frac{0.2378 - 0.0238UTCI}{1 + e^{-(2.99 - 0.16 \cdot UTCI)}} + 0.1308UTCI - 3.4646 \quad (29)$$

$$MTSV_{D_W} = \sum_{1=1}^{3} MTSV_{Dw=i} \times P_{Dw=i} = \frac{0.0197UTCI - 0.0255}{1 + e^{-(0.25 \cdot UTCI - 8.28)}} - \frac{0.0224UTCI + 0.1196}{1 + e^{-(5.18 - 0.28 \cdot UTCI)}} + 0.1168UTCI - 3.1360 \quad (30)$$

where $MTSV_{D_S}$ and $MTSV_{D_W}$ are the expected MTSV as functions of UTCI, considering the probability of subjects' sun desirability and wind desirability, respectively, at varying UTCI.

Figure 7 shows the fitted MTSV versus UTCI obtained from Eq. (16) and the expected MTSV against UTCI obtained from Eqs. (29) and (30). In Figure. 7, blacks plots are the fitted MTSV versus UTCI, and the red and blue plots are $MTSV_{D_S}$ and $MTSV_{D_W}$ versus UTCI, respectively. Because the maximum value of MTSV is 3, the calculated expected MTSV of greater than 3 were altered to 3. It can be seen that there is no difference between the expected MTSV and fitted MTSV until UTCI reaches 30.0°C. As UTCI is higher than 30.0°C, the expected MTSV is higher than the fitted MTSV. As discussed in section 3.3, this is perhaps due to the increased difference in thermal sensations of subjects caused by different sun or wind desirabilities with increasing UTCI, which lead to the probability-weighted average value of TSVs different from the MTSVs. Nevertheless, the agreement of the expected MTSV with the surveyed MTSV at varying UTCI indicated by R^2 of 0.72 is better than that of fitted MTSV with the surveyed MTSV indicated by R^2 of 0.66. These results demonstrate that effects of microclimate environments on subjects estimated by UTCI most likely to lead to the expected MTSV of subjects. Therefore, an acceptable UTCI range of 20.0–32.5℃ can be determined by excepted MTSV between -1 and 1.

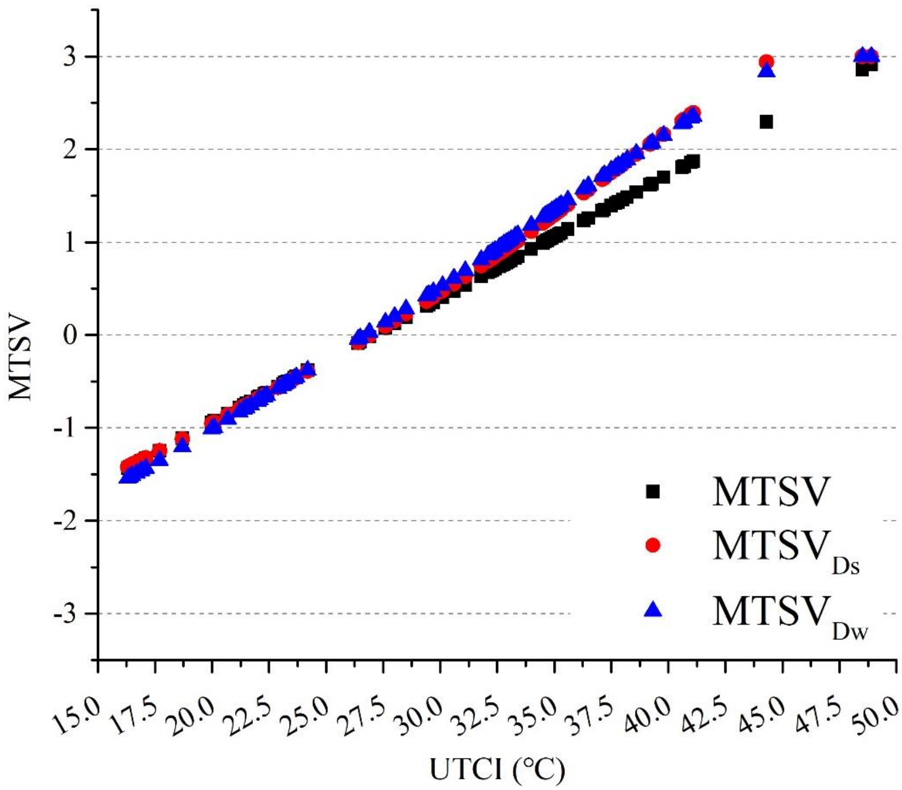


Fig. 7. Fitted MTSV and expected MTSV ($MTSV_{D_S}$ and $MTSV_{D_W}$) versus UTCI

3.5 Investigation of sun acceptability (A_S) and wind acceptability (A_W)

As introduced in section 2.3.4, A_S and A_W are derived based on subjects' sun and wind desirability and overall thermal comfort votes, and suggest whether the effects of the present sun or wind conditions can be accepted at each UTCI value. Questionnaire results were grouped by $D_S = i, (i = 1,2,3)$ or $D_W = i, (i = 1,2,3)$. The percentage of surveyed TCV reported as neutral (0), comfortable (1), and very comfortable (2) was calculated for each group to define acceptable and unacceptable sun and wind conditions for subjects with certain D_S or D_W. The results are summarized in Tables 5 and 6.

Table 5. Percentage of surveyed TCV for each group of D_S and the definition of acceptable or unacceptable sun conditions for each group

Sun desirability $D_S = i, (i = 1,2,3)$	Percentage of TCV		Sun acceptability $A_{S,i\ (i=1,2,3)}$
	-2, -1	0,1,2	
$D_S = 1$	72.40%	27.60%	$A_{S,1} = -1$
$D_S = 2$	13.10%	86.90%	$A_{S,2} = 1$
$D_S = 3$	17.80%	82.20%	$A_{S,3} = 1$

Table 6. Percentage of surveyed TCV for each group of D_W and the definition of acceptable or unacceptable wind conditions for each group

Wind desirability $D_W = i, (i = 1,2,3)$	Percentage of TCV		Wind acceptability $A_{W,i\ (i=1,2,3)}$
	-2, -1	0,1,2	
$D_W = 1$	59.60%	40.40%	$A_{W,1} = -1$
$D_W = 2$	7.00%	93.00%	$A_{W,2} = 1$
$D_W = 3$	55.80%	44.20%	$A_{W,3} = -1$

In Table 5, the percentage of surveyed TCV of 0, 1, and 2 is less than 80% for $D_S = 1$ group, indicating unacceptable effects of the sun condition on subjects desiring less sun; the $A_{S,1}$ is equal to -1. The percentage of surveyed TCV of 0, 1, and 2 is greater than 80% for $D_S = 2$ and $D_S = 3$ groups, demonstrating the acceptable effects of the sun conditions on subjects desiring more sun or no change of sun; $A_{S,2}$ and $A_{S,3}$ are both equal to 1. In Table 6, the percentage of surveyed TCV of 0, 1, and 2 is greater than 80% only for $D_S = 2$ group, indicating that effects of the corresponding wind conditions are only acceptable on subjects voting for $D_W = 2$; $A_{W,2}$ is assigned a value of 1. The percentage of surveyed TCV of 0, 1, and 2 are less than 50% for $D_W = 1$ and $D_W = 3$ group. Although around 40% of subjects selecting $D_W = 1$ and $D_W = 3$ reported TCV of 0, 1, and 2, the effects of the wind conditions were considered unacceptable for these subjects and need to be improved as they desire; $A_{W,1}$ and $A_{W,3}$ are both equal to -1. Accordingly, once subjects desire a change in the wind conditions, the effects of the wind conditions on them are said to be unacceptable, suggesting that subjects are more strict to wind conditions than sun conditions.

With $A_{S,i\ (i=1,2,3)}$, $A_{W,i\ (i=1,2,3)}$, $P_{Ds=i}$, and $P_{Dw=i}$ versus UTCI known, A_S and A_W at varying UTCI can be determined by the probability-weighted average value of $A_{S,i\ (i=1,2,3)}$ or $A_{W,i\ (i=1,2,3)}$ calculated for each UTCI using Eqs. (31) and (32).

$$A_S = A_{S,1} \cdot P_{Ds=1} + A_{S,2} \cdot P_{Ds=2} + A_{S,3} \cdot P_{Ds=3} = 1 - 2 \times \frac{1}{1+e^{-(0.28 \cdot UTCI - 9.88)}} \quad (31)$$

$$A_W = A_{W,1} \cdot P_{Dw=1} + A_{W,2} \cdot P_{Dw=2} + A_{W,3} \cdot P_{Dw=3} = 1 - 2 \times \left(\frac{1}{1+e^{-(5.18 - 0.28 \cdot UTCI)}} + \frac{1}{1+e^{-(0.25 \cdot UTCI - 8.28)}}\right) \quad (32)$$

The distributions of A_S and A_W versus UTCI are shown in Figure. 8. Values of A_S and A_W between -1 and 1 at varying UTCI indicate the expected degree of acceptability of the sun and wind conditions affecting on subjects under a thermal stress represented by UTCI. For UTCI values with A_S or A_W of greater than 0, the effects of the corresponding wind or sun conditions on subjects can be accepted. The effects of the wind or sun conditions are unacceptable at UTCI where A_S or A_W are less than 0. The black curve in Figure. 8 shows the distribution of A_S versus UTCI. It can be observed that A_S decreases with increasing UTCI, and effects of sun conditions become unacceptable for UTCI over 35.0°C. This is due to the increasing probability of subjects voting for $D_S = 1$ as UTCI increases. As $P_{Ds=1}$ is greater than 50% for a UTCI value, the effects of the corresponding sun conditions at this UTCI are unacceptable. Because UTCI of less than 16.5°C were not observed in this study, acceptable microclimate environments where effects of sun conditions are acceptable for subjects are determined for the UTCI range of 16.5–35.0°C. The red curve in Figure. 8 shows the distribution of A_W versus UTCI. Unlike A_S, A_W initially increases and then decreases with increasing UTCI, and the maximum A_W is observed at a UTCI of 26.0℃. This is due to the increase in $P_{Ds=2}$ with increasing UTCI from 16.5℃ to 26.0℃, and the decrease in $P_{Ds=2}$ with UTCI higher than 26.0℃. The acceptable UTCI range of 18.5–32.5℃ where the effects of wind conditions are acceptable is determined by the intersection between the red curve and the 0 acceptability line.

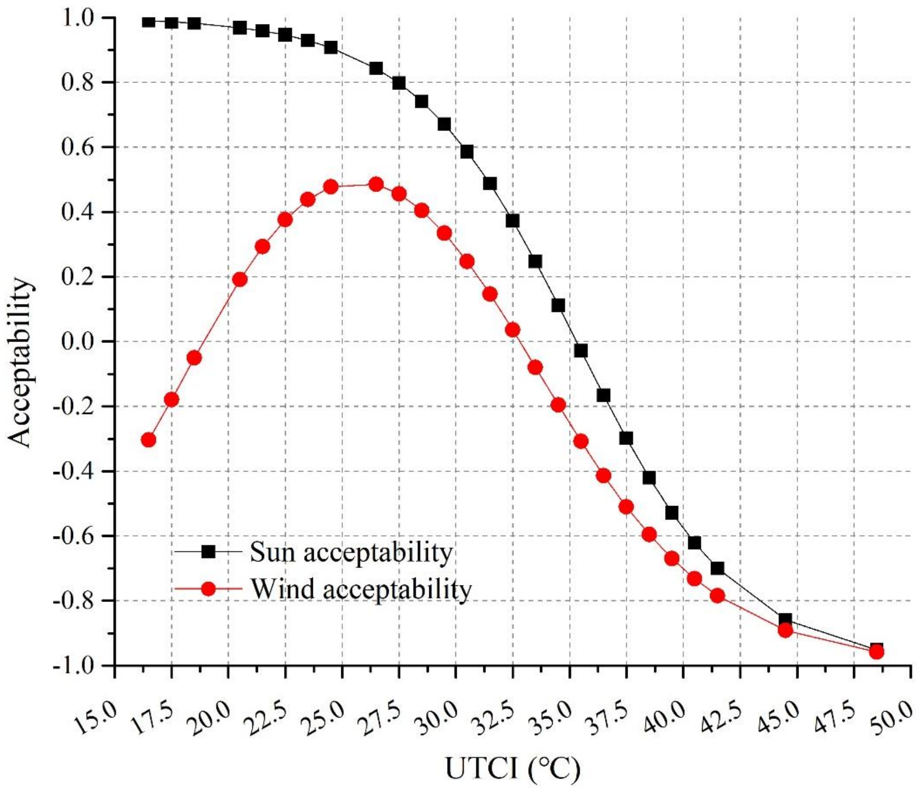


Fig. 8 Sun and wind acceptability versus UTCI

From Figure. 8, acceptable wind conditions existed in the UTCI range of 18.5–32.5℃ while acceptable sun conditions are observed under a larger UTCI range of 16.5–35.0℃. This means that once the UTCI value falls between 32.5℃ and 35.0℃ in one outdoor place surveyed, it is indicated that the corresponding wind conditions of this place are unacceptable even though the corresponding sun conditions are still acceptable. ~~acceptable wind conditions are observed under a narrow UTCI range, and acceptable sun conditions are found under a larger UTCI range.~~ Additionally, A_S is greater than A_W for any UTCI value. For the same UTCI value which indicates the same thermal stress, effects of sun conditions are more acceptable by subjects than those of wind conditions. The relative influences of sun and wind conditions on subjects at each UTCI can then be realized by comparing A_S and A_W . A significant difference between A_S and A_W is observed in the UTCI range of 16.5–26.0℃, suggesting more acceptable effects of sun conditions felt by subjects. While A_W rapidly increases from -0.3 to 0.5 with increasing UTCI, A_S decreases slightly from 1.0 to 0.8. Considering that the expected MTSV discussed in Section 3.4 increases with increasing UTCI, it can be verified that effects of varying wind speeds reflected by A_W in this UTCI range are predominant on thermal sensations of subjects. Therefore, wind conditions play a dominant role on subjects for UTCI of less than 26.0℃, whereas the effects of sun conditions on subjects are stable.

At UTCI of higher than 26.0℃, although A_S is greater than A_W , the difference between A_S and A_W decreases with increasing UTCI, and the black curve representing A_S is sharper than the red curve representing A_W with varying UTCI. The result is that the degree of sun acceptability and wind acceptability perceived by subjects are significantly different initially, and sun conditions are much more acceptable than wind conditions. However, as the UTCI increases, this difference becomes small, and the degree of acceptability of sun conditions rapidly decrease, suggesting that subjects are more sensitive to effects of sun conditions with increasing UTCI. Therefore, sun conditions play a dominant role on influencing thermal perceptions of subjects at UTCI of higher than 26.0℃. A fast and effective method to improve outdoor thermal environments with a UTCI value of larger than 26.0℃ is to add shadings and weaken strong sun conditions. Nevertheless, the effects of wind conditions on subjects are always less acceptable than those of sun conditions, and wind conditions should be improved as subjects' desire in any case. The results shown in Fig. 8 can provide intuitive suggestions for urban designers for optimizing wind or sun conditions to improve thermal comfort at a given UTCI.

Except for suggestions for optimizing wind or sun conditions, acceptable UTCI ranges of 16.5–35.0℃ and 18.5–32.5℃ determined by A_S and A_W of higher than 0, respectively, are also helpful for urban design. The acceptable UTCI range where wind conditions are acceptable is lower than that where sun conditions are acceptable, which indicates less satisfaction of subjects with effects of wind conditions than with sun conditions. Additionally, in the warm-biased conditions corresponding to the UTCI range from 32.5℃ and 35.0℃ in Hong Kong, it seems that people felt warm primarily because they felt that there was a lack of breeze rather than to blame the sun. ~~Therefore~~In general, to achieve acceptable outdoor thermal environments by urban designers, acceptable UTCI range with acceptable sun conditions should be satisfied by urban interventions at least.

As discussed in Section 3.4, another acceptable UTCI range of 20.0℃-32.5℃ is determined by expected MTSV values of between -1 and 1. It is interesting to note that a larger acceptable UTCI range was determined using A_S and A_W than the expected MTSV. As indicated by the correlation between the UTCI and expected MTSV shown in Fig. 7, the expected MTSV corresponding to the UTCI ranges determined with the A_S and A_W is slightly outside the range of -1 to 1. These results suggest that microclimate environments where subjects' thermal sensations are slightly higher than 1 (slightly warm) or lower than -1 (slightly cool) can still be acceptable as a result of acceptable sun or wind conditions of those microclimate environments. Therefore, an acceptable UTCI range or microclimate environment can be determined by different principles. If there is a high requirement of outdoor thermal comfort in a place, the acceptable UTCI range determined by expected MTSV should be controlled. Otherwise, microclimate environments can be accepted by subjects as long as the corresponding UTCI ranges are acceptable UTCI ranges with acceptable sun or wind conditions which can be satisfied by urban interventions.

4. Conclusions

This study conducted an advanced assessment of outdoor thermal comfort through simultaneous physical measurements and questionnaire surveys. The surveyed thermal sensations and sun and wind desirability responding to the UTCI was discussed, and the influences of sun and wind conditions on subjects at varying UTCI were intuitively revealed via the sun and wind acceptability parameter in this study. The following conclusions can be drawn:

- The surveyed thermal sensation responding to the UTCI depends on the desirability of sun and wind conditions (D_S and D_w) of subjects. Subjects desiring more sun or less wind felt significantly cooler than subjects desiring less sun or more wind at the same UTCI value. This is due to subjects' psychological attitudes toward sun and wind conditions or the stronger sensitivity of subjects to sun and wind conditions than that of the UTCI. Additionally, differences in thermal sensations caused by wind desirability are larger than those caused by sun desirability.

- The probability of subjects' D_S and D_w fit well with the UTCI in logistic regressions. The expected MTSV versus UTCI determined considering the effects of D_S and D_w on thermal sensations and P_{Ds} and P_{Dw}versus UTCI is better agreed with the surveyed MTSV than the fitted MTSV obtained from the direct linear regression between the UTCI and surveyed MTSV does. Effects of microclimate environments on subjects estimated by UTCI most likely to lead to the expected MTSV.
- The acceptability of sun and wind conditions for subjects (A_S and A_W , respectively) were derived from D_S, D_w, and TCV, and intuitively reveal the influences of sun and wind conditions on subjects with varying UTCI. Acceptable UTCI ranges of 16.5–35.0°C and 18.5–32.5°C are determined by acceptable sun conditions and wind conditions respectively. For UTCI of lower than 26.0°C, wind conditions were dominant in influencing subjects' thermal perception. The change of wind speed is effective to change thermal perceptions under this condition. In contrast, the effects of sun conditions on subjects were dominant at UTCI of greater than 26.0°C, and a fast and effective method to improve outdoor thermal comfort is to change wind conditions. Nevertheless, the effects of wind conditions were less satisfied by subjects than those of sun conditions and needed to be modified in any case.

It should be cautioned that the conclusions given in this study may not be universally suitable for different groups of people, as the study was done for young and middle-aged people in a particular subtropical climate region. The results of this study can provide useful information for urban designers to determine how to improve outdoor thermal comfort and suggest further outdoor thermal comfort studies.

Reference

1. Akbari, H., et al., *Local climate change and urban heat island mitigation techniques–the state of the art.* Journal of Civil Engineering and Management, 2016. **22**(1): p. 1-16.
2. Chen, L. and E. Ng, *Outdoor thermal comfort and outdoor activities: A review of research in the past decade.* Cities, 2012. **29**(2): p. 118-125.
3. Johansson, E. and R. Emmanuel, *The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka.* International journal of biometeorology, 2006. **51**(2): p. 119-133.
4. Krüger, E., P. Drach, and P. Broede, *Outdoor comfort study in Rio de Janeiro: site-related context effects on reported thermal sensation.* International Journal of Biometeorology, 2017. **61**(3): p. 463-475.

5. Ali-Toudert, F. and H. Mayer, *Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate.* Building and environment, 2006. **41**(2): p. 94-108.
6. Shashua‐Bar, L., D. Pearlmutter, and E. Erell, *The influence of trees and grass on outdoor thermal comfort in a hot‐arid environment.* International Journal of Climatology, 2011. **31**(10): p. 1498-1506.
7. Lin, T.-P. and A. Matzarakis, *Tourism climate and thermal comfort in Sun Moon Lake, Taiwan.* International Journal of Biometeorology, 2008. **52**(4): p. 281-290.
8. Nikolopoulou, M. and S. Lykoudis, *Thermal comfort in outdoor urban spaces: analysis across different European countries.* Building and Environment, 2006. **41**(11): p. 1455-1470.
9. Spagnolo, J. and R. De Dear, *A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia.* Building and environment, 2003. **38**(5): p. 721-738.
10. Lai, D., et al., *Studies of outdoor thermal comfort in northern China.* Building and Environment, 2014. **77**: p. 110-118.
11. Niu, J., et al., *A new method to assess spatial variations of outdoor thermal comfort: Onsite monitoring results and implications for precinct planning.* Building and Environment, 2015. **91**: p. 263-270.
12. Höppe, P., *The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment.* International journal of Biometeorology, 1999. **43**(2): p. 71-75.
13. Bröde, P., et al., *Deriving the operational procedure for the Universal Thermal Climate Index (UTCI).* International journal of biometeorology, 2012. **56**(3): p. 481-494.
14. Huizenga, C., Z. Hui, and E. Arens, *A model of human physiology and comfort for assessing complex thermal environments.* Building and Environment, 2001. **36**(6): p. 691-699.
15. Pickup, J. and R. De Dear, *An outdoor thermal comfort index (OUT-SET*) - Part I - The model and its assumptions.* Biometeorology and Urban Climatology at the Turn of the Millennium, 2000: p. 279-283.
16. normalisation, O.i.d., *Moderate Thermal Environnements: Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort*. 1984: International Organization for Standardization.
17. Höppe, P., *Different aspects of assessing indoor and outdoor thermal comfort.* Energy and buildings, 2002. **34**(6): p. 661-665.
18. Huang, T., et al., *Simultaneous environmental parameter monitoring and human subject survey regarding outdoor thermal comfort and its modelling.* Building and Environment, 2017. **125**: p. 502-514.
19. Lin, T.P., R. de Dear, and R.L. Hwang, *Effect of thermal adaptation on seasonal outdoor thermal comfort.* International Journal of Climatology, 2011. **31**(2): p. 302-312.
20. Lin, C.-H., T.-P. Lin, and R.-L. Hwang, *Thermal comfort for urban parks in subtropics: understanding visitor's perceptions, behavior and attendance.* Advances in Meteorology, 2013. **2013**.
21. Lam, C.K.C., A.J. Gallant, and N.J. Tapper, *Perceptions of thermal comfort in heatwave and non-heatwave conditions in Melbourne, Australia.* Urban Climate, 2016.

22. Nikolopoulou, M. and K. Steemers, *Thermal comfort and psychological adaptation as a guide for designing urban spaces.* Energy and buildings, 2003. **35**(1): p. 95-101.
23. Xie, Y., et al., *Evaluation of a multi-nodal thermal regulation model for assessment of outdoor thermal comfort: Sensitivity to wind speed and solar radiation.* Building and Environment, 2018. **132**: p. 45-56.
24. Ali-Toudert, F. and H. Mayer, *Effects of asymmetry, galleries, overhanging facades and vegetation on thermal comfort in urban street canyons.* Solar Energy, 2007. **81**(6): p. 742-754.
25. Hong, B. and B. Lin, *Numerical studies of the outdoor wind environment and thermal comfort at pedestrian level in housing blocks with different building layout patterns and trees arrangement.* Renewable Energy, 2015. **73**: p. 18-27.
26. Lin, B., et al., *Numerical simulation studies of the different vegetation patterns' effects on outdoor pedestrian thermal comfort.* Journal of Wind Engineering and Industrial Aerodynamics, 2008. **96**(10): p. 1707-1718.
27. Yang, W., N.H. Wong, and S.K. Jusuf, *Thermal comfort in outdoor urban spaces in Singapore.* Building and Environment, 2013. **59**: p. 426-435.
28. Walton, D., V. Dravitzki, and M. Donn, *The relative influence of wind, sunlight and temperature on user comfort in urban outdoor spaces.* Building and environment, 2007. **42**(9): p. 3166-3175.
29. Lin, T.-P., et al., *Quantification of the effect of thermal indices and sky view factor on park attendance.* Landscape and Urban Planning, 2012. **107**(2): p. 137-146.
30. Liu, J., et al., *Detached eddy simulation of pedestrian-level wind and gust around an elevated building.* Building and Environment, 2017. **125**: p. 168-179.
31. Du, Y., et al., *Effects of lift-up design on pedestrian level wind comfort in different building configurations under three wind directions.* Building and Environment, 2017. **117**: p. 84-99.
32. Hwang, R.-L. and T.-P. Lin, *Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions.* Architectural Science Review, 2007. **50**(4): p. 357-364.
33. Yang, W., N.H. Wong, and G. Zhang, *A comparative analysis of human thermal conditions in outdoor urban spaces in the summer season in Singapore and Changsha, China.* International Journal of Biometeorology, 2013. **57**(6): p. 895-907.
34. Lin, T.-P., *Thermal perception, adaptation and attendance in a public square in hot and humid regions.* Building and environment, 2009. **44**(10): p. 2017-2026.
35. Mansfeld, Y., A. Freundlich, and H. Kutiel, *The relationship between weather conditions and tourists' perception of comfort: the case of the winter sun resort of Eilat.* Climate change and tourism–assessment and coping strategies. Maastricht, 2007: p. 116-139.
36. Handbook, A., *Fundamentals.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 2017.
37. Jendritzky, G., A. Maarouf, and H. Staiger. *Looking for a universal thermal climate index (UTCI) for outdoor applications*. in *Windsor-conference on thermal standards*. 2001.
38. Blazejczyk, K., et al., *An introduction to the universal thermal climate index (UTCI).* 2013.
39. Havenith, G., et al., *The UTCI-clothing model.* International journal of biometeorology, 2012. **56**(3): p. 461-470.

40. Błażejczyk, K., et al., *Principles of the new Universal Thermal Climate Index (UTCI) and its application to bioclimatic research in European scale.* Miscellanea Geographica, 2010. **14**(2010): p. 91-102.
41. Kántor, N., A. Kovács, and T.-P. Lin, *Looking for simple correction functions between the mean radiant temperature from the "standard black globe" and the "six-directional" techniques in Taiwan.* Theoretical and applied climatology, 2015. **121**(1-2): p. 99-111.
42. Bröde, P., et al., *Calculating UTCI equivalent temperature.* Environmental Ergonomics XIII, University of Wollongong, Wollongong, 2009: p. 49-53.
43. Dayton, C.M., *Logistic regression analysis.* Stat, 1992: p. 474-574.
44. Fanger, P., *Thermal comfort analysis and application in environmental design.* Mac Graw Hill, 1972.
45. St, L. and S. Wold, *Analysis of variance (ANOVA).* Chemometrics and intelligent laboratory systems, 1989. **6**(4): p. 259-272.
46. Johnson, D.H., *The insignificance of statistical significance testing.* The journal of wildlife management, 1999: p. 763-772.
47. Craparo, R.M., *Significance level.* Encyclopedia of measurement and statistics, 2007. **3**: p. 889-891.

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