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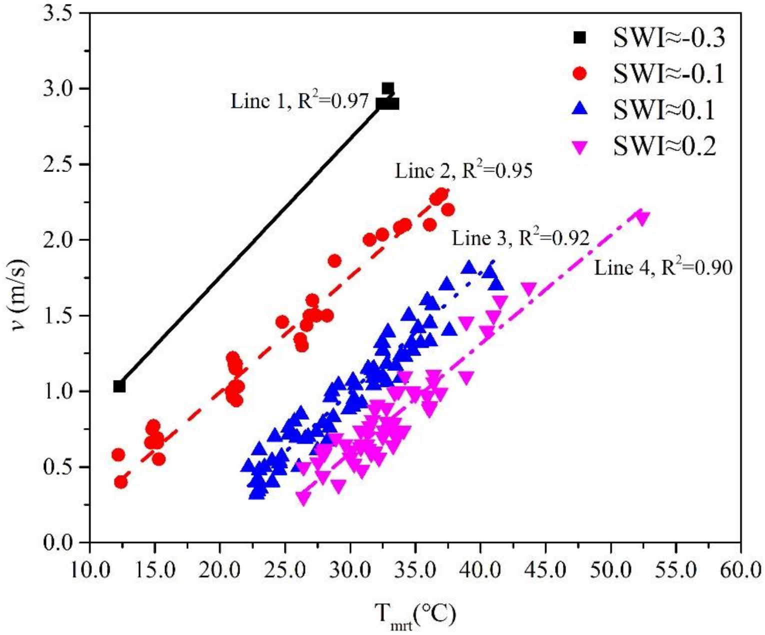
Exploration of applicability of UTCI and thermally comfortable sun and wind conditions outdoors in a subtropical city of Hong Kong

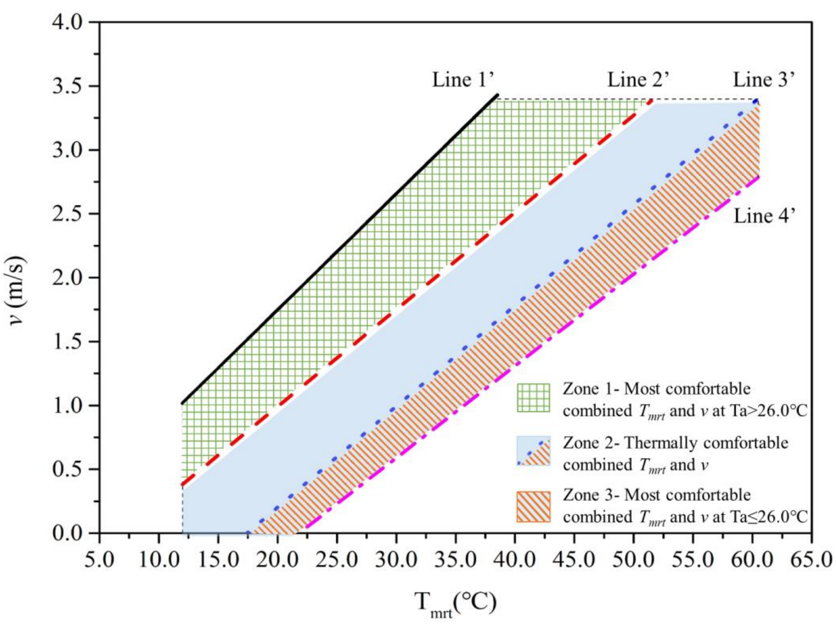
Abstract

This study conducted simultaneous physical measurements and questionnaire surveys to study the outdoor thermal comfort in the subtropical, high-density Hong Kong. With an innovative analysis method, the study reveals that mean radiant temperature (T_{mrt}), sun and wind desirability, and wind speed (v) were the top three factors influencing the surveyed thermal sensation vote (TSV), which was not well estimated by the Universal Thermal Climate Index (UTCI); and that UTCI underestimated the effects of v and T_{mrt} at higher air temperatures (T_a) but overestimated the impacts of T_a and relative humidity on TSV of subjects in Hong Kong. Accordingly, a combined sun and wind condition index (SWI) was defined to explore the combined effects of T_{mrt} and v on thermal comfort. Within the meteorological parameter ranges of $12.0 \leq T_{mrt} \leq 64.0$°C, $0 < v \leq 4.0$m/s, and $12.0 \leq T_a \leq 36.0$°C, over 50% of the subjects voted comfortable within the SWI range of -0.1-0.2; and the SWI range of -0.3-(-0.1) and that of 0.1-0.2 were more comfortable at $T_a > 26.0$°C and $T_a \leqslant 26.0$°C, respectively. A v-T_{mrt} diagram was thus constructed to indicate the comfort zones of sun and wind combinations, which can be used to estimate the comfort levels of outdoor space in the design stage.

Graphical Abstracts



(a)



(b)

Thermally comfortable combinations of sun and wind conditions at T_a ranging from 12.0℃ to 36.0℃: a) coordinate graph of v and T_{mrt}; b) v-T_{mrt} diagram and comfort zone

Keywords: Outdoor thermal comfort; Universal thermal climate index (UTCI); Thermal sensation votes; Wind speed; Mean radiant temperature; Combined Sun and Wind Conditions Index (SWI)

Nomenclature

PET   Physiological Equivalent Temperature

UTCI   Universal Thermal Climate Index

OUT_SET*   Standard Effective Temperature for Outdoor

SVF   Sky View Factor

UEB   Underneath-elevated-building

T_a Air temperature, °C

T_g Globe temperature, °C

v Wind speed

v_{10} Wind speed at 10 m

RH   Relative humidity, %

Q_s Short-wave irradiance, W/m^2

Q_l Long-wave irradiance, W/m^2

T_{mrt} Mean radiant temperature, °C

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

I_{clo} Clothing insulation

M Metabolic rate, Met

TSV Thermal Sensation Vote

TCV Thermal Comfort Vote

D_S Sun desirability

D_W Wind desirability

$D_{S/W}$ Sun and wind desirability (ratio of D_S and D_W)

SWI Combined Sun and Wind Conditions Index

T_{mrt}’ Standardized T_{mrt}

v’ Standardized v

MTSV Mean Thermal Sensation Vote

MTSV’ Standardized MTSV

UTCI’ Standardized UTCI

VIF Variance Inflation Factor

R^2 Coefficient of Determination

1. Introduction

According to the fifth assessment report proposed by the Intergovernmental Panel on Climate Change (IPCC) in 2014, the future climate change would be resulted from the increasing emission of carbon dioxide caused by anthropogenic activities [1]. The global warming included in the climate change process will bring heat wave and increase the annual mean air temperature [2], which in turn affects the outdoor thermal environment perceived by a person [3]. Under the context of global warming, the effects of urban heat island particularly during hot days can further jeopardizes the outdoor thermal comfort [4, 5]. This situation prevents citizens from enjoying outdoor activities and brings economic and social problems to the sustainable urban development [6]. Therefore, appropriate environmental design in urban areas by evaluating the outdoor thermal conditions is essential for relieving the adverse effects of climate change and urban heat island, and ensuring the quality of outdoor thermal environment for the sustainable urban development [7].

Over the years, most of outdoor thermal comfort studies have been focused on outdoor thermal comfort evaluation using the thermo-physiological indices, such as the physiological equivalent temperature (PET) [8], universal thermal climate index (UTCI) [9], or the standard new effective temperature (SET*) [10]. Among these indices, UTCI is the latest and more sophisticated thermal index developed using the multi-node and multi-segment Fiala thermo-physiological model [11] and has been applied in many climate regions [12]. The applicability of UTCI was usually validated using linear regression analysis between surveyed thermal sensations and UTCI values [13-16]. A significant deviation of surveyed thermal sensations corresponded to one UTCI value has been found during validations and explored to be resulted from various urban morphology cues [17], anthropometric variables [18], and psychological factors such as thermal adaptation in different seasons [14] and individual sun and wind desirability [19]. These factors were found influencing subjective thermal sensations but have not been considered by UTCI [20, 21], which reflects some limitations of UTCI in accurately predicting outdoor thermal sensations.

Besides the evaluation of outdoor thermal conditions with indices, many studies have furtherly explored approaches to improve outdoor thermal conditions in urban areas [22, 23]. According to previous studies, sun and wind conditions were found as the important factors influencing the thermal sensation outdoors [24-26], and the modifications of sun or wind conditions by building morphology and green infrastructure are thought as effective approaches to improve outdoor thermal comfort [27-31]. Sun conditions can be modified by shades and the higher shades level in summer can increase the more thermal comfort [3, 32, 33]. Wind conditions can be modified by suitable designs of buildings, spaces and roads [34, 35] and the amplified wind speed is efficient to increase thermal comfort in urban areas on hot days [36-38]. According to Edward et al., wind speed of larger than 1.5m/s at pedestrian level was required to achieve outdoor thermal comfort in Hong Kong [39].

The constrains of existing studies are as follows:

Firstly, none existing studies have explored the applicability or limitations of UTCI by comparing the sensitivity of UTCI and that of subjective thermal sensation to the meteorological and personal parameters. Additionally, the understanding of the deviation between the outdoor thermal effects evaluated by UTCI and those directly perceived by thermal sensation is essential for the further improvement of the UTCI. However, the knowledge of such deviation and the information of what aspects of UTCI can be improved for better evaluation of outdoor thermal comfort are limited, especially in subtropical climate regions like Hong Kong.

Secondly, although previous studies have indicated that suitable urban design can modify sun or wind conditions for thermal comfort, single modification of sun or wind conditions and inappropriate modifications may not effectively satisfy comfort requirements of citizens. The appropriate combinations of sun and wind conditions, which are not intuitively reflected by thermal indices like UTCI, are more efficient and immediate to create comfortable outdoor space. These combinations are instructive for the sustainable urban design and friendly for citizens to experience outdoor environments. However, the assessments of the outdoor thermal comfort in the respective of combined sun and wind conditions have been seldom conducted, leading to a limited knowledge of thermally comfortable combination of sun and wind conditions.

Therefore, the objectives of this study in corresponding to the above raised challenges are:

1) To compare the influences of meteorological and personal factors estimated by UTCI and those evaluated by thermal sensations of people in Hong Kong,

2) To explore the aspects of UTCI to be improved for better thermal sensation predictions,

3) To evaluate outdoor thermal comfort in Hong Kong in respective of the combined sun and wind conditions with a new proposed index, and.

4) To explore how to properly combine the sun and wind conditions to achieve thermal comfort in the urban-design stage under global warming conditions.

2. Methodology

2.1 Field survey

The field surveys including simultaneous microclimate monitoring and questionnaire survey were conducted in a university campus in Hong Kong under different weather types of summer, autumn, and winter during March 2016 to March 2018. The total four typical outdoor sites were selected throughout the campus based on having various microclimate environments (Fig. 1), including OPEN area (Site 1) which are exposed to the direct and reflected radiation, semi-OPEN area under various large trees (Site 2) or translucent glass awnings (Site 3), and the UEB area (Site 4) which is the podiums beneath elevated teaching buildings. The field surveys in the OPEN and UEB areas were respectively conducted on 29 and 27 days of given months during March 2016 to March 2018, and those in the semi-OPEN areas were conducted on 7 days during November 2017 to March 2018. For the field survey at each site, subjects were asked to experience microclimate environments for 15 min and then fill in the questionnaire. Simultaneously, the microclimate parameters of this site were monitored. Around six sets of a filed survey were conducted in different sites during 13:00-15:00 pm on a typical day of a given month.

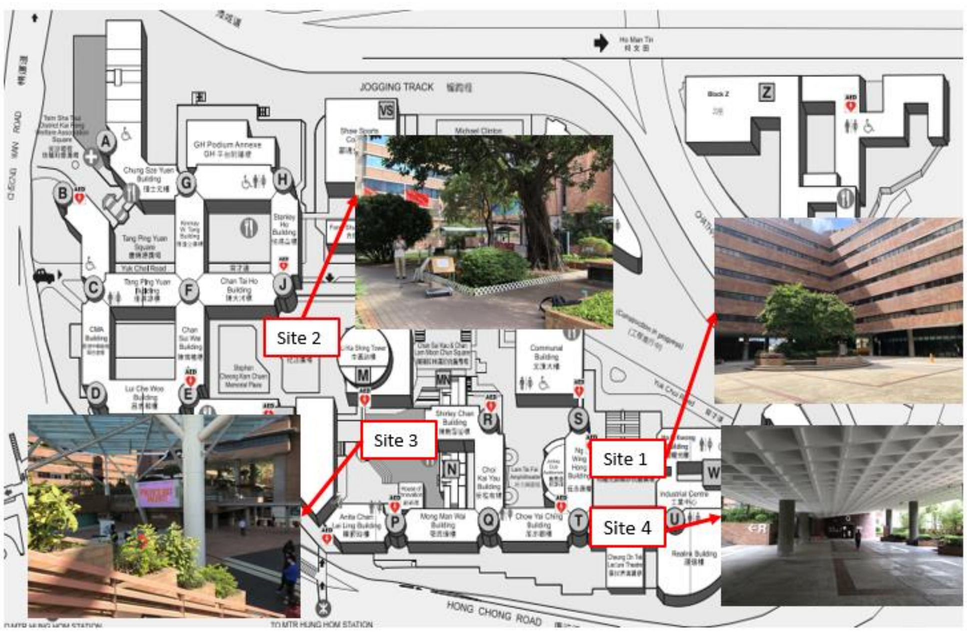


Fig. 1 Selected outdoor places for the field survey

2.1.1 Microclimate monitoring

The major microclimate parameters including air temperature (T_a, °C), relative humidity (RH, %), wind speed (v, m/s), short-wave and long-wave radiation (Q_s and Q_l, W/m^2) were measured by mini weather station shown as in Fig. 2. The net radiometers (CNR4, KIPP&ZONEN) on the station were used to capture short-wave and long-wave radiations from six directions (north-south, east-west, and up-down). A most advanced omnidirectional ultrasonic anemometer (81000, R.M. YOUNG) was used to measure the wind speed and wind direction. T_a and RH were measured by R.M.YOUNG 41382. Values of all meteorological parameters were recorded by instruments every 10 seconds during the field tests. The specifications of measurements instruments are listed in the Table. 1 [40]. The mini weather station was set at 1.5 m above the floor to measure the microclimate parameters at the pedestrian level.

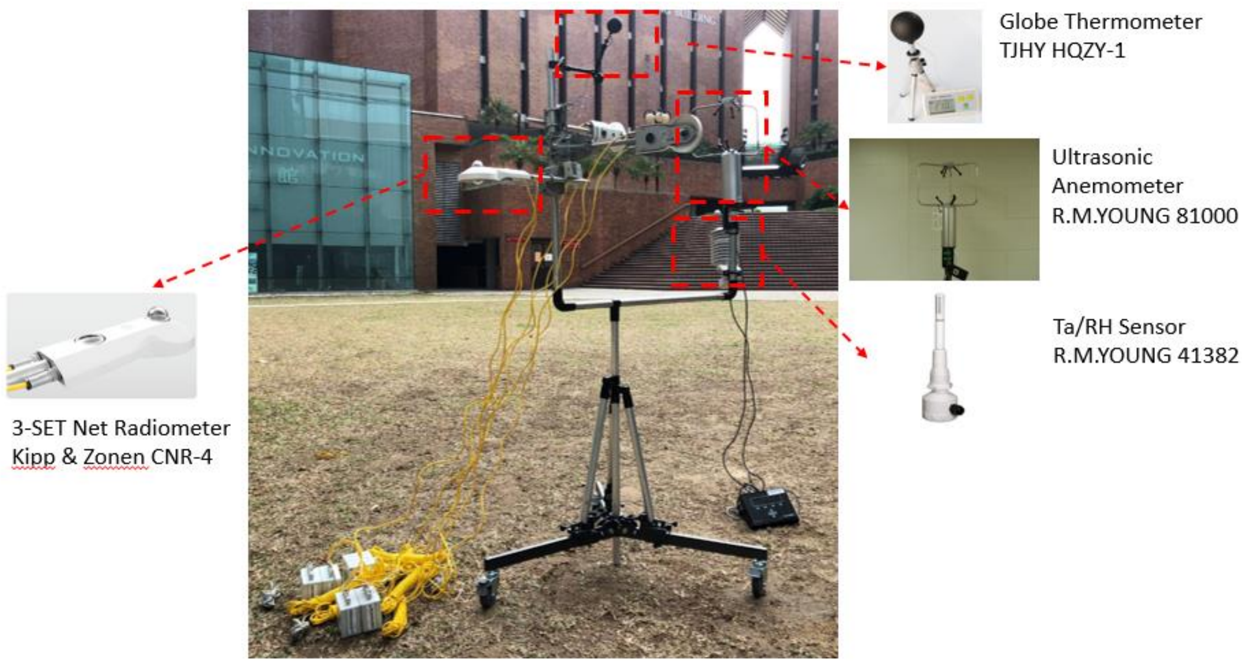


Fig. 2 Mini weather station with instruments for measuring meteorological parameters

Table 1 Specifications of measurement instruments

Instrument	Meteorological parameter	Measuring Range	Accuracy
R.M.YOUNG 41382	Air temperature (T_a)	-50-50 (℃)	±0.3℃

	Relative humidity (*RH*)	0-100 (%)	±1%
R.M.YOUNG 81000	Wind speed (*v*)	0-40 (m/s)	±0.05m/s
TJHY HQZY-1	Globe temperature (T_g)	-40-60 (℃)	±0.3℃
Kipp & Zonen CNR-4	Long-wave irradiance (Q_l)	-250-250 (W)	<10%
	Short-wave irradiance (Q_s)	0-2000 (W)	<5%

2.1.2 Questionnaire survey

The questionnaire concerned about the personal information and subjective thermal perceptions responding to microclimate environments and 1638 questionnaire samples were collected in this study. The collected questionnaire samples in four sites were 564 (Site 1), 184 (Site 2), 184 (Site 3) and 706 (Site 4), respectively. Subjective thermal perceptions is consisting of thermal sensation vote (TSV) scaled by ASHARE 7-point [41], the desirability of changing or maintaining wind or sun conditions scaled by 3-point and thermal comfort vote (TCV) scaled by 5-point. Personal information includes the age, gender, clothing status, and activity level. Subjects in this study were all Chinese adults recruited from the university with the average age of 28. They were told to wear suitable clothes according to the air temperature on the survey day and conducted mild activities (sitting, standing, and strolling) as they want during the tests. Clothing status and activity level can be quantitatively transferred to the clothing insulation (I_{clo}) and metabolic rate (*M*) based on ASHRAE standard 55 [41] and ISO standard 7730 [42]. The collected average clothing insulation is 0.53clo with the standard deviation of 0.25clo, and the collected average metabolic rate is 1.18M with the standard deviation of 0.19M. The questions related to the thermal perceptions discussed in this study were designed in English and Chinese versions and shown in the Fig. 3.

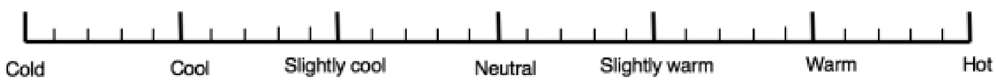
1. What do you want to change for sunlight

Less sunlight (1)	No change needed (2)	More sunlight (3)

2. What do you want to change 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)

a)

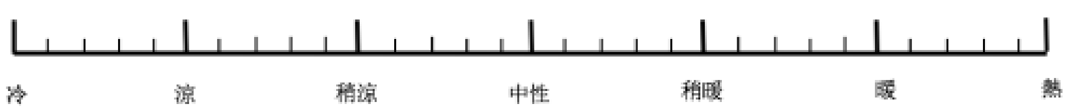
1. 你对目前室外的日照有何要求?

更少日照 (1）	日照无需改变(2)	更多日照(3)

2. 你对目前室外的风环境该有何要求?

更弱的风(1)	风无需改变(2)	更强的风(3)

3. 在当前著装下，在尺规上标记你的热感觉



4. 你将会如何描述总体的热环境?

非常不舒适(-2)	不舒适 (-1)	中性(0)	舒适(1)	非常舒适(2)

b)

Fig. 3 Questions concerning subjects' thermal perceptions: a) English version; b) Chinese version

In question 1, "sunlight (日照)" represents sun conditions covering light and heat effects of the sun and "wind (风)" in the question 2 represents wind conditions which reflect convective cooling effects of the wind speed. Answers to questions 1 and 2 are denoted as subjects' sun desirability (D_S) and wind desirability (D_W) respectively. Less sunlight desired ($D_S=1$), no changes in sunlight desired ($D_S=2$) and more sunlight desired ($D_S=3$) are answers for question 1. Less wind desired ($D_W=1$), no changes in wind desired ($D_W=2$) and more wind desired ($D_W=3$) are answers for question 2. Answers to questions 3 and 4 are the thermal sensation vote (TSV) and overall thermal comfort vote (TCV), respectively.

2.2 Data analysis

2.2.1 Thermal comfort assessing index

Universal Thermal Climate Index (UTCI) was applied in this study to evaluate outdoor thermal comfort in the subtropical Hong Kong. It is defined as the isothermal air temperature of the reference environment that would produce the same dynamic response (strain) of the physiological model as that produced under actual environment. Such reference environment is characterized with the relative humidity of 50%, calm air and radiant temperature equaling to air temperature [12]. The advanced clothing model predicting the clothing insulation based on the air temperature is coupled with the "Fiala" model of UTCI [43]. Additionally, the metabolic rate of the multi-node model of UTCI is assumed to be a constant value of 2.3 Met which is similar to that of people who walk outdoors [9]. Given all of these, UTCI is the function of only four meteorological parameters including T_a, RH, v_{10}, and T_{mrt}, which can be expressed as the Eq. (1) and calculated by RaymanPro software package.

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

To calculate the UTCI, mean radiant temperature (T_{mrt}) which reflects the radiant heat transfer in a human body is required [41]. It can be calculated using the six-directional radiations collected from field surveys (Eq. 2), which is verified as the most accurate method to obtain the T_{mrt} in the microclimate environments [44].

$$T_{mrt} = \sqrt[4]{\sum_{i=1}^{6} \frac{W_i(\alpha_k Q_s + \varepsilon_p Q_l)}{\varepsilon_p \sigma} - 273.1} \qquad (2)$$

The explanation of this equation can be referred to a previous study conducted by Xie et al. [24].

Wind speed at 10m above ground (v_{10}) is another required input for the calculation of UTCI. Since the wind speed (v) in this study is measured at a pedestrian level of 1.5m above ground, v needs to be converted to v_{10} using Eq. 3 [9].

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

where x is the height of the mini weather station, and 1.5 m was adopted for x in this study.

2.2.2 Sun and wind desirability ($D_{S/W}$)

As introduced in Section 2.1.2, there are three votes for the sun desirability (D_S): $D_S=1$, $D_S=2$, and $D_S=3$, and three votes for the wind desirability (D_W): $D_W=1$, $D_W=2$, and $D_W=3$. To simultaneously reflect the desire of subjects to change or maintain the sun and wind conditions, the ratio of D_S and D_W votes ($D_{S/W}$) was determined for each questionnaire. The values and the corresponding explanations of the ordered categorical variable $D_{S/W}$ are listed in Table 2. In Table 2, $D_{S/W} \leq 0.7$ demonstrates subjects' desire for either more wind speed and/or less sunlight, and $D_{S/W} \geq 1.5$ indicates subjects' desire for either more sunlight and/or less wind speed. $D_{S/W}$=1.0 only reflects subjects' desire for no changes in wind and sun conditions ($D_S=2$, $D_W=2$) due to no simultaneously observed desires for less wind ($D_S=1$) and less sunlight ($D_W=1$) or more wind ($D_W=3$) and more sunlight ($D_S=3$).

Table. 2 Value of $D_{S/W}$ and the corresponding explanation

$D_{S/W}$	Explanation
0.3	Desire for less sunlight ($D_S=1$) and more wind ($D_W=3$)
0.5	Desire for less sunlight ($D_S=1$) and no change of wind ($D_W=2$)
0.7	Desire for no change in sunlight ($D_S=2$) and more wind ($D_W=3$)
1.0	Desire for no change in sunlight ($D_S=2$) and wind ($D_W=2$)
1.5	Desire for more sunlight ($D_S=3$) and no change in wind ($D_W=2$)
2.0	Desire for no change in sunlight ($D_S=2$) and less wind ($D_W=1$)
3.0	Desire for more sunlight ($D_S=3$) and less wind ($D_W=1$)

The $D_{S/W}$ reflecting subjects' desirability of sun and wind conditions is not only resulted from the physical effects of sun and wind conditions but also the individual preference and purpose. For example, people who prefer sunlight will desire more sunlight outdoors than those who hate the sunlight. Such desirability might in turn influence subjects' thermal perceptions outdoors, for example, people who desire more sunlight feel cooler than those who desire less sunlight responding to the same sun conditions [19]. Therefore, in this study, $D_{S/W}$ is regarded as an essential personal factor in assessments of outdoor thermal comfort and indicator for exploring the combined sun and wind conditions for thermal comfort.

2.2.3 Multiple linear regression analysis

The effects of meteorological parameters (T_a, RH, v, and T_{mrt}) and personal parameters (I_{clo}, M, and $D_{S/W}$) on surveyed thermal sensations and those estimated by UTCI, were compared using the multiple linear regression analysis [45]. The multiple linear regression analysis was conducted by relating these parameters to surveyed thermal sensations and UTCI in the software SPSS 24.0. The stepwise regression method [45] was adopted to avoid the collinearity of parameters and select the significant parameters determining the subjective TSV and UTCI.

The absolute values of standardized coefficients [46] of parameters obtained from the regression analysis were used to rank the importance of parameters influencing subjective TSV or estimated by UTCI. The parameter weight analysis was derived from the index weight analysis [47] which analyzes the weight of different indices in multi-criteria synthetically assessment of a system. In other words, index weight analysis is to determine the relative influences of different indices in the synthetical assessment. Similar as one of the calculations of the index weight [48], the parameter weight was calculated by dividing the absolute value of a parameter's standard coefficient by sum of absolute values of all parameters' standard coefficients. Accordingly, parameter weight is to reveal the relative influences of different parameters in subjective TSV and those estimated by UTCI.

2.2.4 Data standardization

In this study, two data standardization methods were adopted for the data analysis [49]. One is the Z-core standardization method expressed by Eq. (4) and is used for comparing variations of the UTCI and the surveyed TSV with changes in meteorological and personal parameters. This standardization method adjusts data with different units or measured on different scales to dimensionless data with the same zero-mean and unit-variance. Due to the standardization, the variations of the UTCI and those of the surveyed TSV with changing parameters can be compared. This method is also the default method in the multiple linear regression analysis to standardize UTCI and surveyed TSV mentioned in 2.2.3.

$$\mathrm{X}' = \frac{X-\mu}{\sigma} \tag{4}$$

where X' is the standardized value of X; μ is the mean value of X in a dataset and σ is the standard deviation of X in a dataset.

The other one is the 0-1 scaling standardization method expressed as Eq. (5). It is used for combining the wind speed (v) and the mean radiant temperature (T_{mrt}) to reflect the combined sun and wind conditions. This standardization method transfers data with different units or measured on different scales to data ranging from 0 to 1. This method can not only combine the variables such as v and T_{mrt} using the mathematical method but also reflect the relative strength of v and T_{mrt}.

$$\mathrm{X}' = \frac{X-X_{min}}{X_{max}-X_{min}} \tag{5}$$

where X' is the standardized value of X; X_{min} is the minimum value of X in a dataset and X_{max} is the maximum value of X in a dataset.

3 Results and Discussion

3.1 Meteorological conditions

Table 3 summarizes the microclimate conditions collected in four sites during the field survey days. It can be seen that the average T_a and T_a range are similar in Site 1 (OPEN area) and Site 4

(UEB area), while Site 1 has a higher average T_{mrt} and a larger T_{mrt} range than the Site 4 does. Additionally, lower and more stable wind speeds are observed in Site 1 than those in Site 4.

On average, the T_a in Site 2 (area under tree shades) and Site 3 (area under glass awnings) are 27.5℃ and 21.2℃, respectively. Lower average T_{mrt} and larger average v are investigated in Site 3 than those in Site 2. It is perhaps due to different field survey days conducted in Sites 2 and 3, or Site 3 with a basin type is characterized by low T_{mrt} and high v. Wide ranges of meteorological parameters reflecting the climate features of Hong Kong were collected in this study with T_a from 11.9℃ to 36.2℃, T_{mrt} from 12.0℃ to 64.0℃, v from 0.3m/s to 3.8m/s, and RH from 35% to 93%.

Table. 3 Microclimate conditions collected in this study

Sites	Time period	No. of days	Air temperature (T_a, ℃)				Mean radiant temperature (T_{mrt}, ℃)				Wind speed (v, m/s)				Relative humidity (RH, %)			
			Min	Max	Mean	Sd.	Min	Max	Mean	Sd.	Min	Max	Mean	Sd.	Min	Max	Mean	Sd.
Site 1 (OPEN)	30/3/2016-9/3/2018	29	12.1	36.2	26.5	5.4	14.1	64.0	40.0	12.9	0.4	2.2	1.0	0.4	35.0	92.8	59.5	13.5
Site 2 (Tree shade)	10/11/2017-9/3/2018	7	24.5	29.1	27.5	0.9	27.9	54.9	34.2	5.7	0.3	2.3	1.1	0.5	35.4	72.7	48.5	16.0
Site 3 (Glass awnings)	3/11/2017-2/3/ 2018	7	17.7	29.2	21.2	3.7	21.0	49.1	29.0	7.2	0.3	3.8	1.1	0.8	41.8	73.6	57.7	10.7
Site 4 (UEB)	30/3/2016-9/3/2018	27	11.9	34.0	27.0	4.6	12.1	39.5	28.3	5.8	0.3	3.3	1.6	0.9	39.7	92.0	66.8	12.7

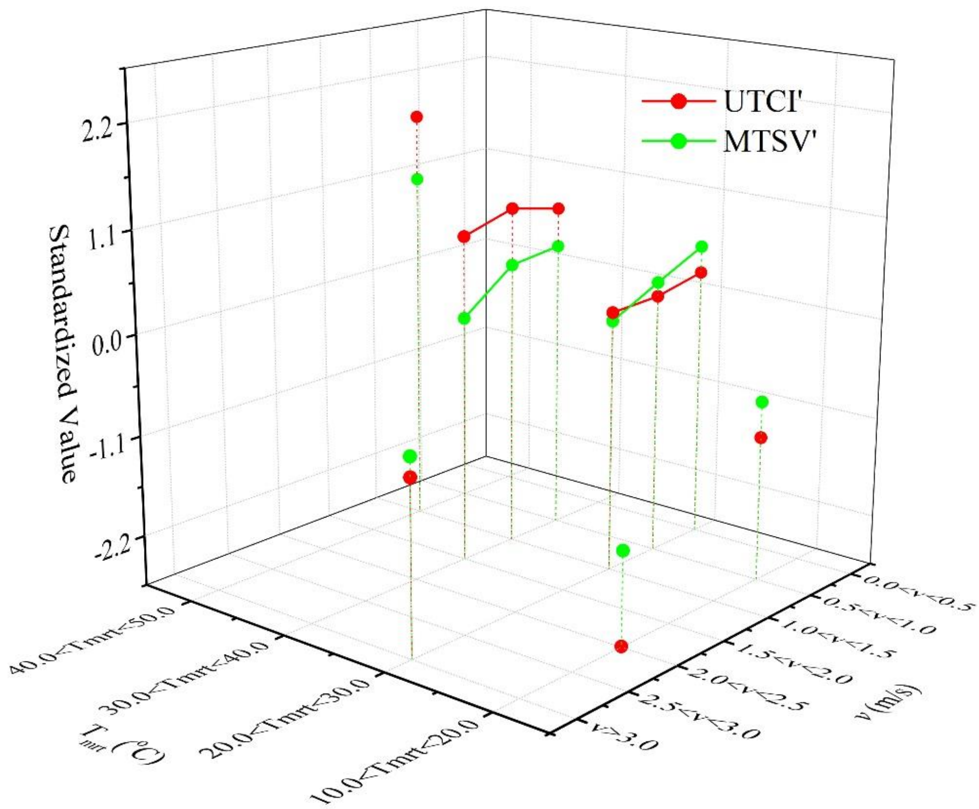
3.2 Variations of UTCI and surveyed TSV with changes in meteorological parameters

As introduced in section 2.1, microclimate monitoring and questionnaire survey were conducted simultaneously. The surveyed TSVs were firstly grouped by three air temperature ranges:

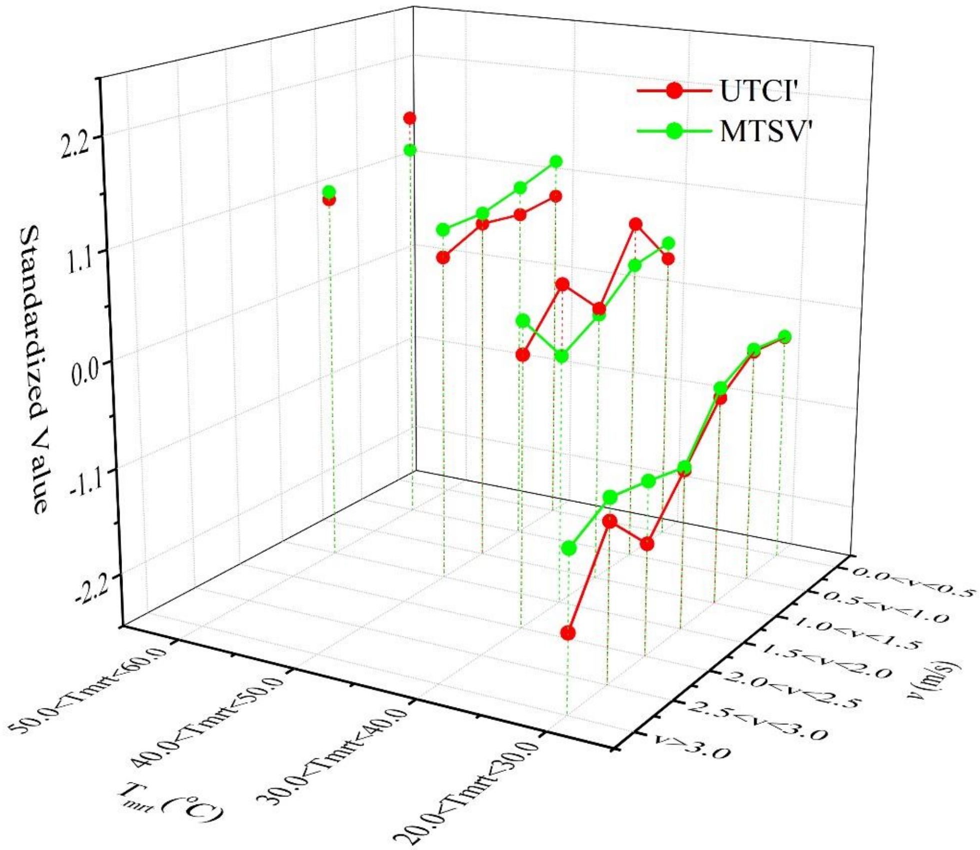
$T_a \leq 20.0$°C, 20.0°C$< T_a \leq 30.0$°C, and $T_a > 30.0$°C. For each air temperature range, surveyed TSVs were grouped into five mean radiant temperature (T_{mrt}) ranges: $10.0 < T_{mrt} \leq 20.0$°C, $20.0 < T_{mrt} \leq 30.0$°C, $30.0 < T_{mrt} \leq 40.0$°C, $40.0 < T_{mrt} \leq 50.0$°C and $50.0 < T_{mrt} \leq 60.0$°C. Last, in any one T_{mrt} range, the surveyed TSVs were averaged for each wind speed range: $0.0 < v \leq 0.5$m/s, $0.5 < v \leq 1.0$m/s, $1.0 < v \leq 1.5$m/s, $1.5 < v \leq 2.0$m/s, $2.0 < v \leq 2.5$m/s, $2.5 < v \leq 3.0$m/s, and $v > 3.0$m/s. In each combination of T_a, T_{mrt}, and v ranges, the corresponding recorded meteorological parameters were averaged to calculate the average UTCI value. The average UTCI values and average surveyed TSVs (MTSVs) were then standardized using the Z-score method. The standardized average UTCI (UTCI') and the standardized MTSV (MTSV') at varying of T_{mrt}, v, and T_a were thus compared with each other in Fig. 4.

Fig. 4a shows the variations of the UTCI' and MTSV' versus T_{mrt} and v at $T_a \leq 20.0$°C. The discrepancy between the UTCI' and MTSV' at varying of T_{mrt} and v is significant. The trends of the UTCI' and MTSV' reveal that UTCI' is more sensitive to T_{mrt} than the MTSV' be at similar wind speed ranges. Fig. 4b depicts the variations of UTCI' and MTSV' with changes in v and T_{mrt} at 20.0°C$< T_a \leq 30.0$°C. The discrepancy between the UTCI' and MTSV' at varying of v and T_{mrt} is smaller than that observed at $T_a < 20.0$°C. Even so, the UTCI' seems to be more sensitive to v than the MTSV' be at T_{mrt} of lower than 40.0°C.

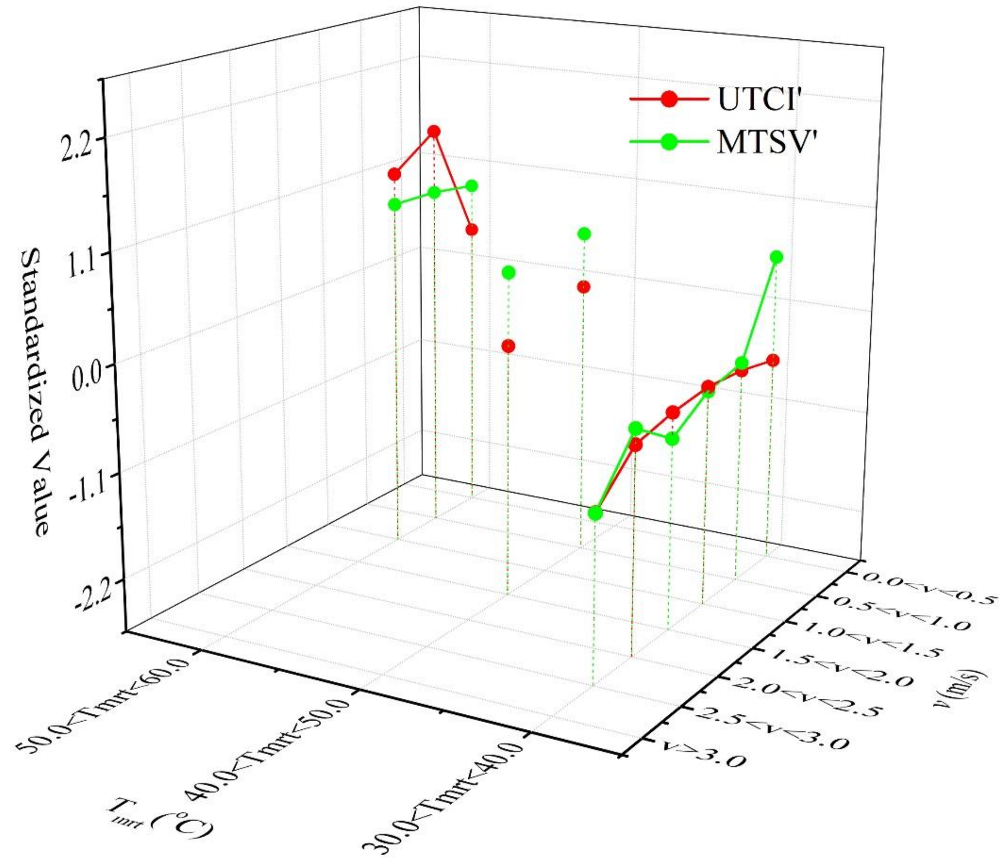
Fig. 4c displays the variations of the UTCI' and MTSV' against v and T_{mrt} under $T_a > 30.0$°C. It can be seen that the UTCI' increases slowly at first and then rapidly with increasing T_{mrt}, which is opposite to the variation of the MTSV'. At high T_a, MTSV' seems to be more sensitive to the T_{mrt} than the UTCI' be as T_{mrt} is lower than 50.0°C. Additionally, at T_{mrt} of lower than 40.0°C, the MTSV' shows more sensitivity to v than the UTCI' does. In summary, the UTCI' and MTSV' exhibit different variations with changes in T_a, T_{mrt}, and v. It is assumed that the effects of T_a, T_{mrt}, and *v* estimated by UTCI are deviated from those evaluated by subjective TSV. However, this assumption needs to be furtherly validated by statistical analysis because the UTCI and subjective TSV are not only determined by T_{mrt}, *v*, and T_a.



(a)


UTCI'
MTSV'
Standardized Value
2.2
1.1
0.0
-1.1
-2.2
50.0<Tmrt<60.0
40.0<Tmrt<50.0
30.0<Tmrt<40.0
20.0<Tmrt<30.0
T_{mrt} (°C)
0.0<v<0.5
0.5<v<1.0
1.0<v<1.5
1.5<v<2.0
2.0<v<2.5
2.5<v<3.0
v>3.0
v (m/s)

(b)



(c)

Fig. 4. Variations of the UTCI' and MTSV' against T_{mrt} and v at different T_a ranges: a) $T_a \leq 20.0$°C; b) 20.0°C$<T_a \leq 30.0$°C; c) $T_a > 30.0$°C

3.3 Effects of factors evaluated by surveyed TSV and those estimated by UTCI

The effects of meteorological parameters (T_a, T_{mrt}, v, and RH) and personal parameters (I_{clo}, M, and $D_{S/W}$) evaluated by TSV and those estimated by UTCI, were compared in this section using the multiple linear regression analysis. The values of parameters were averaged for each 15 min field test, and the averaged meteorological parameters were used to calculate the UTCI. The surveyed TSVs after each 15 min and the calculated UTCI thus corresponded to the same averaged values of parameters. These parameters were then correlated with the UTCI and surveyed TSVs, respectively, and Table 4 shows the stepwise regression results at T_a≤20.0℃. The parameters in Table 4 are all significant parameters determining subjective TSV and UTCI after stepwise regression analysis. The variance inflation factor (VIF) values indicate no collinearity among parameters in Table 4. The standardized coefficient and parameter weight are obtained after the standardization of UTCI and surveyed TSV in the regression analysis. The larger parameter weight indicates the more important influence of a parameter in the subjective TSV and that estimated by UTCI.

From Table. 4, it is noted that the subjective TSV is mainly influenced by T_a, $D_{S/W}$, v, and T_{mrt} at T_a≤20.0℃ and the goodness of fit of the regression model is reflected by R^2 of 0.447. R^2 of 0.994 shows the strong correlation between UTCI and T_a, T_{mrt}, v, and RH. According to the standardized coefficient, $D_{S/W}$ has negative effects on the TSV. It is demonstrated that subjects feel hot as they desire more wind or/and less sunlight and feel cold as they desire less wind or/and more sun. Based on the absolute values of standardized coefficients and parameter weights, T_a is the major factor influencing the subjective TSV and followed by $D_{S/W}$, whereas influences of T_{mrt} estimated by UTCI are crucial. The results agree with the observations in Fig. 4a that UTCI' is more sensitive to the T_{mrt} than the MTSV' be at T_a≤20.0℃. In summary, at T_a≤20.0℃, the influences of RH and T_{mrt} in subjective TSV are less significant than those estimated by UTCI, and influences of the $D_{S/W}$ are not considered by UTCI.

Table. 4 Multiple linear regression analysis for the UTCI and surveyed TSV at T_a≤20.0℃

Surveyed TSV/UTCI	**Parameters**	**R^2**	**Standardized Coefficients**	**Parameter weight**	**Sig.**	**Collinearity Statistics (VIF)**

Surveyed TSV	(Constant)				0.000	
	T_a		0.380	38.1%	0.000	1.981
	$D_{S/W}$	0.447	-0.242	24.3%	0.001	1.417
	v		-0.197	19.7%	0.007	1.450
	T_{mrt}		0.178	17.8%	0.041	2.090
UTCI	(Constant)				0.000	
	T_{mrt}		0.589	36.9%	0.000	2.086
	T_a	0.994	0.426	26.7%	0.000	2.047
	v		-0.440	27.6%	0.000	1.561
	RH		0.140	8.8%	0.000	1.750

Table. 5 shows the stepwise regression results at 20.0°C<T_a≤30.0°C. The subjective TSV is mainly influenced by $D_{S/W}$, T_a, T_{mrt}, v, and I_{clo} at this T_a range, and the effects of I_{clo} are less important based on its standardized coefficient. R^2 of the regression models for the surveyed TSV and UTCI are 0.575 and 0.990, respectively. Indicated by the parameter weights, T_{mrt} turns to be the major factor influencing the subjective TSV, whereas effects of T_a estimated by UTCI become crucial. Similar variations of the MTSV' and UTCI' in Fig. 4b might be caused by similar integrated effects of parameters felt by subjects and those estimated by UTCI, regardless of the individual influences of these parameters in the subjective TSV and those estimated by UTCI. Even so, subjects are less sensitive to *RH* and T_a than the UTCI be at 20.0°C<T_a≤30.0°C, and the influences of $D_{S/W}$ are not considered by UTCI as well.

Table. 5 Multiple linear regression analysis for the UTCI and surveyed TSV at 20.0°C<T_a≤30.0°C

UTCI/ Surveyed TSV	**Parameters**	**R^2**	**Standardized Coefficients**	**Parameter weight**	**Sig.**	**Collinearity Statistics (VIF)**
Surveyed TSV	(Constant)	0.575			0.000	
	T_{mrt}		0.502	50.6%	0.000	1.895
	$D_{S/W}$		-0.227	22.8%	0.000	1.635
	v		-0.132	13.3%	0.000	1.205
	T_a		0.082	8.3%	0.005	2.290
	I_{clo}		0.049	5.0%	0.031	1.382
UTCI	(Constant)	0.990			0.000	
	T_a		0.548	38.9%	0.000	1.709
	T_{mrt}		0.453	32.3%	0.000	1.934
	v		-0.225	16.2%	0.000	1.170
	RH		0.176	12.7%	0.000	1.160

Table. 6 shows the stepwise regression results at T_a>30.0℃. R^2 of the regression models for the surveyed TSV and UTCI are 0.495 and 0.956, respectively. It is interesting to note that effects of RH estimated by UTCI have become predominant at high T_a. However, RH has not been verified to influence the subjective TSV based on the regression results. At T_a>30.0℃, the influences of T_{mrt} and v in the subjective TSV are more significant than those estimated by UTCI based on the parameter weights. Therefore, with the same changes in T_{mrt} or v, larger variation of the TSV than that of the UTCI can be observed in Fig. 4c.

Table. 6 Multiple linear regression analysis for the UTCI and surveyed TSV at T_a>30.0℃

UTCI/ Surveyed TSV	Parameters	R^2	Standardized Coefficients	Parameter weight	Sig.	Collinearity Statistics (VIF)
Surveyed TSV	(Constant)	0.495			0.001	
	T_{mrt}		0.488	53.7%	0.000	1.715
	D_S/D_W		-0.163	17.9%	0.001	1.516
	v		-0.146	16.1%	0.001	1.246
	M		0.112	12.3%	0.005	1.036
UTCI	(Constant)	0.956			0.000	
	RH		0.551	30.9%	0.000	1.619
	T_{mrt}		0.544	30.6%	0.000	2.776
	T_a		0.530	29.7%	0.000	3.216
	v		-0.155	8.8%	0.000	1.337

Indicated by R^2 values in Tables 4-6, the relationship between the parameters and the surveyed TSV is weaker than that between the parameters and the UTCI. It can be interpreted that unlike UTCI, the subjective TSV might be not only influenced by discussed meteorological and personal parameters but also by other unexplored parameters. Beyond that, influences of discussed parameters in subjective TSV are different from those estimated by UTCI. According to the parameter weights, the influence of T_{mrt} in the subjective TSV increases with increasing T_a, and subjects are more sensitive to v under T_a>30.0℃ and T_a≤20.0℃ than under 20.0℃<T_a≤30.0℃. However, influences of v and T_{mrt} estimated by UTCI decreases with increasing T_a.

In general, it seems that at higher air temperatures, the influences of *v* and T_{mrt} in subjective thermal sensation are more significant than those estimated by UTCI. Additionally, subjective thermal sensation are not purely influenced by physical effects of T_{mrt} and *v* but also desirability of T_{mrt} and *v*, which is not considered by UTCI. *RH* is significant for determining the UTCI but found less effective in changing TSV. The average RH collected in this study is 61.8% with the standard deviation of 14.3%. It is assumed that subjects' adaptability to humid climate in Hong Kong has made them less sensitive to changes in RH.

Table. 7 shows the stepwise regression results in all collected microclimate environments. Irrespective of the relatively low R^2 of the regression model for the surveyed TSV, it is verified that T_{mrt}, $D_{S/W}$, and *v* are the top three factors influencing the thermal sensation of people conducting moderate activities in outdoor environments in Hong Kong. However, the T_a, T_{mrt}, and *v* are determining parameters estimated by UTCI. Presumably, it is perhaps due to subjects' adaptive clothes-wearing based on air temperature and their short-term and longitude adaptability to subtropical hot-humid climate in Hong Kong, they are less sensitive to T_a than the UTCI be. Thus, it can be seen that a suitable combination of sun and wind conditions in Hong Kong might make people comfortable under a wide air temperature range.

Table. 7 Multiple linear regression analysis for the UTCI and surveyed TSV in all microclimate environments

UTCI/ Surveyed TSV	**Parameters**	**R^2**	**Standardized Coefficients**	**Parameter weight**	**Sig.**	**Collinearity Statistics (VIF)**
Surveyed	(Constant)				0.000	

TSV	T_{mrt}		0.488	48.7%	0.000	2.090
	D_S/D_W		-0.210	21.0%	0.000	1.656
	v	0.610	-0.143	14.2%	0.000	1.178
	T_a		0.122	12.1%	0.000	1.980
	M		0.040	4.00%	0.013	1.030
	(Constant)				0.000	
	T_a		0.670	48.3%	0.000	3.305
UTCI	T_{mrt}		0.377	27.5%	0.000	2.075
	v	0.945	-0.160	12.2%	0.000	1.081
	RH		0.162	12.2%	0.000	1.111

3.4 Exploration of thermally comfortable combinations of sun and wind conditions in Hong Kong

As discussed above, sun and wind conditions have significant influences in outdoor thermal sensations, which is not accurately estimated by UTCI. Therefore, the Combined Sun and Wind Conditions Index (SWI), combining the T_{mrt} and v using the 0-1 scaling standardization method, is developed in this study (Eq.6). The SWI is used to assess the outdoor thermal comfort in respective of the combined sun and wind conditions, and provide guidance on how to combine sun and wind conditions for thermal comfort at a wide air temperature range in urban areas. This index is a supplemental index to assess outdoor thermal comfort in an urban-design-friendly way in Hong Kong.

$$\mathrm{SWI} = T'_{mrt} - v'$$

$$= {T_{mrt} - \mathrm{Min}(T_{mrt})}\Big/_{Max(T_{mrt}) - Min(T_{mrt})} - {v - Min(v)}\Big/_{Max(v) - Min(v)}$$

$$= {T_{mrt} - 12.0}\big/_{64.0 - 12.0} - {v - 0}\big/_{4.0 - 0}$$

$$= \frac{T_{mrt} - 12.0}{52.0} - \frac{v}{4.0} \qquad (6)$$

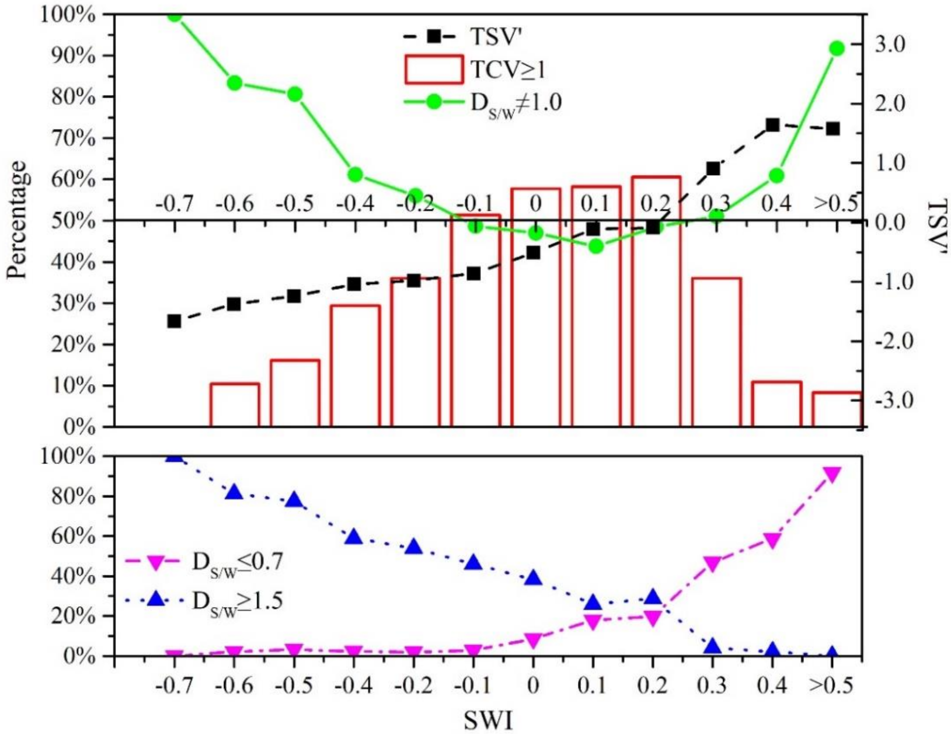
where T'_{mrt} and v' are the standardized T_{mrt} and v, ranging from 0 to 1. The index was applied at the wide range: $12.0 \leq T_{mrt} \leq 64.0$°C and $0 < v \leq 4.0$m/s.

To evaluate outdoor thermal comfort with SWI, the distributions of the surveyed TSV, $D_{S/W}$ and TCV at varying of SWI were investigated in cold conditions ($T_a \leq 26.0$°C) and hot conditions ($T_a > 26.0$°C). Due to limited numbers of subjects for each SWI value, the SWI unit with 0.1 width was chosen for analysis. For example, SWI of 0.1 represented the SWI values equaling to about 0.1, and so on. The surveyed TSVs were averaged for each SWI unit and the averaged TSVs was presented as TSV'. The percentage of $D_{S/W} \leq 0.7$ indicating subjects' desires for either less sunlight and/or more wind, the percentage of $D_{S/W} \geq 1.5$ indicating subjects' desires for either more sunlight and/or less wind, the percentage of $D_{S/W} \neq 1.0$ indicating subjects' desires for changes in sun and wind conditions, and TCV≥1 demonstrating thermal comfort were also calculated for each SWI unit.

Fig. 5a shows the TSV' and percentages of TCV≥1, $D_{S/W} \neq 1.0$, $D_{S/W} \leq 0.7$ and $D_{S/W} \geq 1.5$ against SWI under $T_a \leq 26.0$°C. It can be seen that the TSV' increases with increasing SWI and the percentage of TCV≥1 initially increases with the increasing SWI and then decreases. In this study, the combined sun and wind conditions where more than 50.0% of subjects voted for TCV≥1 were defined as thermally comfortable combined sun and wind conditions. It is due to that more than 80% of subjects feeling comfortable outdoors was difficult to be found in this study. According to

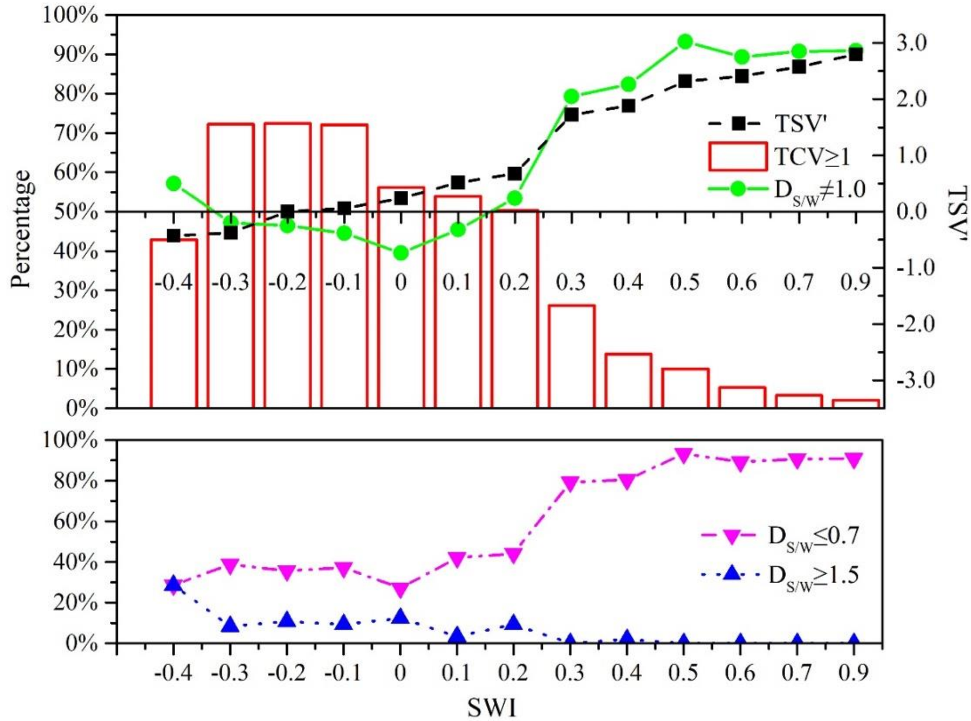
Fig. 5a, at T_a≤26.0°C, the thermally comfortable combined sun and wind conditions are found at SWI range of -0.1-0.2 where TSV' between -1 and 0 (slightly cool and neutral) is observed. The maximum percentage of TCV≥1 is found at SWI range of 0.1-0.2, which is defined as the most comfortable SWI range at T_a≤26.0°C.

Additionally, it is noted that the percentages of $D_{S/W}$≠1.0 increase with the decreasing percentages of TCV≥1. Subjects' desires for either less sunlight and/or more wind ($D_{S/W}$≤0.7) are predominant at higher SWI and those for either more sunlight and/or less wind ($D_{S/W}$≥1.5) are predominant at lower SWI. The results reflect subjects' direct evaluation to sun and wind conditions and their desires of becoming more comfortable by changes in sun and wind conditions. As SWI is higher than 0.3, the sudden decrease of thermal comfort and increase of TSV' and desires for either less sunlight and/or more wind ($D_{S/W}$≤0.7) are observed. Therefore, although still 40%-50% percent of subjects exhibit high expectations of either more sunlight and/or less wind ($D_{S/W}$≥1.5) at the comfortable SWI range, neutral thermal environments with the sun condition slightly stronger than the wind condition are more welcome at T_a≤26.0°C.



TSV'
TCV≥1
D_S/W≠1.0
Percentage
TSV'
D_S/W≤0.7
D_S/W≥1.5
SWI
-0.7 -0.6 -0.5 -0.4 -0.2 -0.1 0 0.1 0.2 0.3 0.4 >0.5

a)



b)

Fig. 5 Averaged thermal sensation (TSV'), percentages of thermal comfort (TCV≥1) and different sun and wind desirability ($D_{S/W}$) at varying of SWI in cold and hot conditions: a) cold conditions (T_a≤26.0°C); b) hot conditions (T_a>26.0°C)

Fig. 5b shows the TSV' and percentages of TCV≥1, $D_{S/W}$ ≠1.0, $D_{S/W}$ ≤0.7 and $D_{S/W}$ ≥1.5 against SWI under T_a>26.0°C. It can be seen that the percentage of TCV≥1 also initially increases with the increasing SWI and then decreases. At T_a>26.0°C, the thermally comfortable combined sun and wind conditions are found at SWI range of -0.3-0.2, and the corresponding TSV' is found between -0.5 and 1 (neutral and slightly warm). It is perhaps due to the effects of air temperature, TSV' in Fig. 5b is higher than that in Fig. 5a as regarding to the same SWI unit. The maximum percentage of TCV≥1 is located at SWI range of -0.3 – (-0.1), which is defined as the most comfortable SWI range at T_a>26.0°C.

It is interesting to note that subjects' desires for either less sunlight and/or more wind ($D_{S/W}$≤0.7) are predominant at almost all SWI at T_a>26.0°C, which is perhaps resulted from the effects air temperature. As SWI is lower than -0.4, the sudden decrease of thermal comfort and increase of desires for either more sunlight and/or less wind ($D_{S/W}$≥1.5) are observed. Therefore, although still 40%-50% percent of subjects show high expectations of either less sunlight and/or more wind ($D_{S/W}$≤0.7) at the comfortable SWI range, neutral thermal environments with the wind condition slightly stronger than the sun condition are more welcome at T_a>26.0°C.

When comparing Fig. 5a and Fig. 5b, comfortable SWI range at T_a>26.0°C (-0.3-0.2) is larger than that at T_a≤26.0°C (-0.1-0.2), indicating the importance of stronger wind conditions in hot days in Hong Kong and relatively high tolerance of subjects with sun conditions. Additionally, the maximum percentage of TCV≥1 observed at T_a>26.0°C is larger than that observed at T_a≤26.0°C. It is perhaps due to that relatively strong wind conditions at T_a>26.0°C not only efficiently take away heat from subjects, but dry moist skin caused by hot-humid days and produce cool stimulus to subjects, which could amplify subjects' comfortable feelings in hot days. However, strong wind conditions at T_a≤26.0°C can bring uncomfortable drafts feelings to subjects. Relatively strong sun conditions in cool days may only increase warm without extra stimulus to subjects as wind conditions do in hot days.

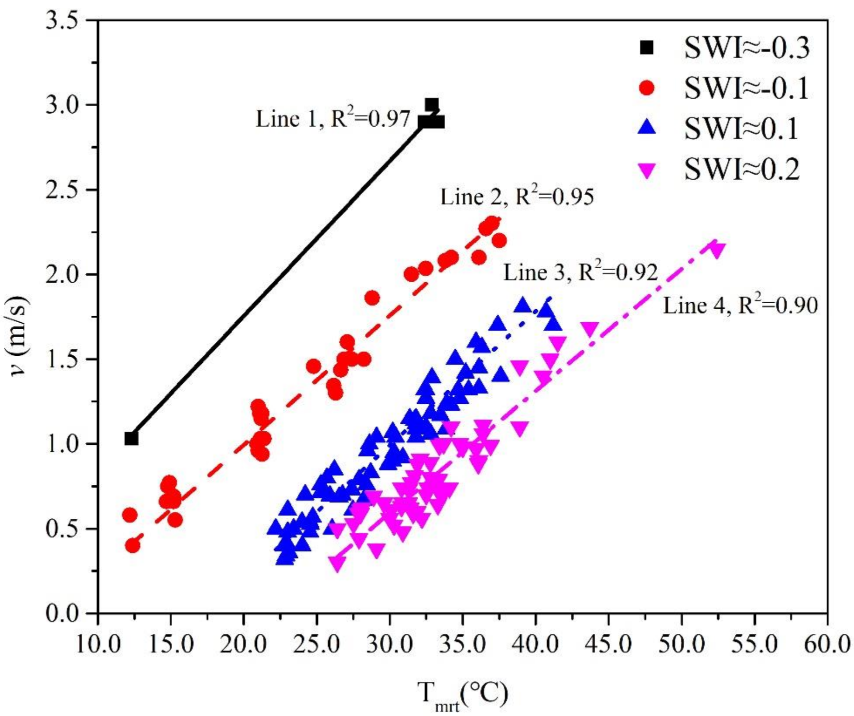
The asymmetrical distributions of TCV≥1 and TSV' against SWI are observed in Fig. 5. When the absolute value of SWI is the same, stronger wind conditions or stronger sun conditions have unequal influence in subjects' thermal comfort. It is perhaps resulted from the integrated effects of the wind, solar radiation, air temperature and the attitudes of subjects to the wind and solar radiation. Additionally, a much sharper decrease of the percentages of TCV≥1 and change of the TSV' at SWI>0.2 than those at SWI<-0.2 is observed. The results reveal that as SWI is out of the comfortable range, subjects are more tolerable to the cooling effects of wind than to the heating effects of solar radiation.

From Fig. 5, the thermally comfortable combinations of sun and wind conditions regarding the SWI range of -0.1-0.2 are found applicable to a wide air temperature range of 12.0℃-36.0℃. Therefore, suitable combinations of sun and wind conditions can help more than 50.0% of people to cope with wide air temperature range and feel comfortable outdoors. Based on the findings above, intuitive guidance on thermally comfortable combinations of sun and wind conditions is provided by Fig. 6.

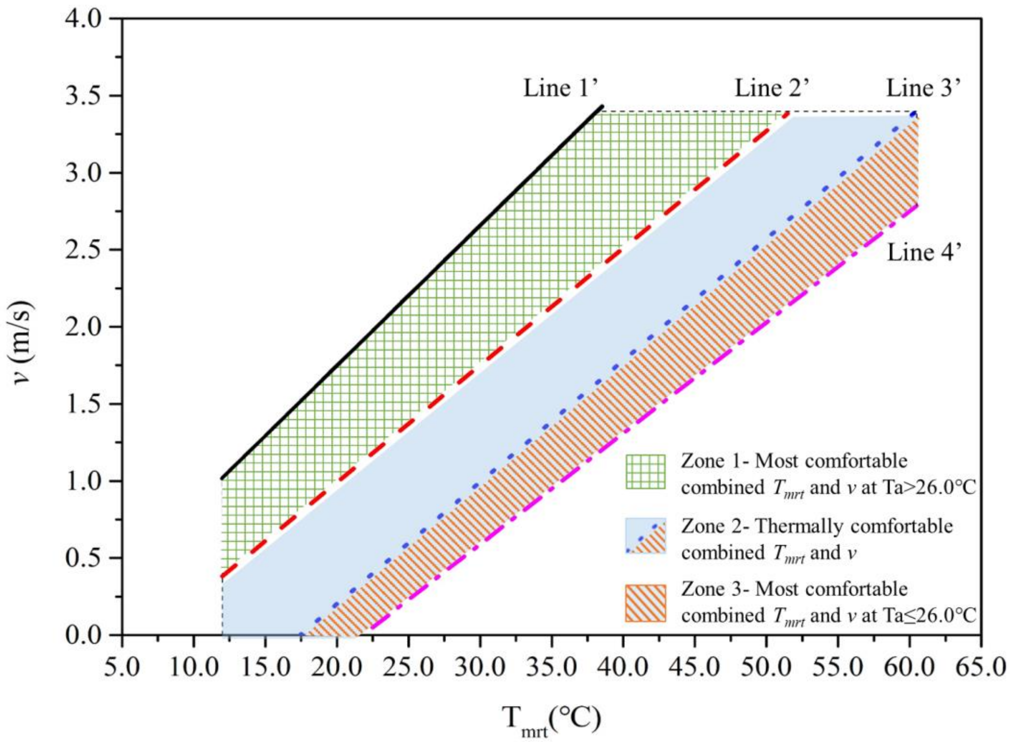
Fig. 6a is a coordinate graph of v and T_{mrt} regarding the SWI units of the thermally comfortable SWI range. Fig. 6b is the v-T_{mrt} diagram for thermal comfort derived from Fig. 6a based on the correlation between v and T_{mrt} in Fig. 6a. The lines 2 and 4 in Fig. 6a are regressed with the point data of SWI≈-0.1 and SWI≈0.2 and expressed as Eqs. (8) and (10), respectively. The parameter ranges of $12.0 \leq T_{mrt} \leq 60.0$℃ and $0<v\leq 3.5$m/s were set and the above two lines were transformed into the lines 2' and 4' in Fig 6b. The lines 2' and 4' are regarded as two benchmarks of thermally comfortable combinations of v and T_{mrt} at T_a range of 12.0-36.0℃. With the other two benchmarks of 3.5m/s for v and 60.0℃ for T_{mrt}, respectively, the thermal comfort zone 2 is drawn in Fig. 6b.

Lines 1 and 3 are regressed with the point data of SWI≈-0.3 and SWI≈0.1 in Fig. 6a, and expressed as Eqs. (7) and (9), respectively. As discussed above, the most comfortable SWI range of -0.3-(-0.1) and that of 0.1-0.2 were found at T_a>26.0℃ and T_a≤26.0℃, respectively. Therefore, in Fig. 6b, the line 1' corresponding to the line 1 and the line 3' corresponding to line 3 are regarded as the lower benchmarks of the most comfortable combinations of v and T_{mrt} at T_a>26.0℃ and

T_a≤26.0℃, respectively. With the benchmarks of 3.5m/s for v and 60.0℃ for T_{mrt}, the comfort zones 1 and 3 are figured out in Fig 6b, respectively.



a)



b)

Fig. 6 Thermally comfortable combinations of sun and wind conditions at T_a ranging from 12.0°C to 36.0°C: a) coordinate graph of v and T_{mrt}; b) v-T_{mrt} diagram and comfort zone

$$\mathrm{v} = 0.091 * T_{mrt} - 0.075 \quad (R^2 = 0.61) \tag{7}$$

$$\mathrm{v} = 0.076 * T_{mrt} - 0.529 \quad (R^2 = 0.81) \tag{8}$$

$$\mathrm{v} = 0.079 * T_{mrt} - 1.378 \quad (R^2 = 0.92) \tag{9}$$

$$\mathrm{v} = 0.072 * T_{mrt} - 1.570 \quad (R^2 = 0.97) \tag{10}$$

The v-T_{mrt} diagram (Fig. 6b) depicts a simplified thermal comfort zone derived from the thermally comfortable combinations of v and T_{mrt} at a wide air temperature range. It can be seen from line 1' to line 4' that effects of v and T_{mrt} make up for each other to keep comfortable thermal environment.

The influences of higher v in subjects can make up the influences of higher T_{mrt} and vice versa. Zone 2 provides useful guidance on how to properly combine v and T_{mrt} to achieve thermal comfort in urban areas under a wide air temperature range. Zone 1 and Zone 3 demonstrate how to furtherly satisfy people by suitable combinations of sun and wind conditions in hot and cold days. It can be seen that the design of outdoor places which can properly combine and control the sun and wind conditions is desired in the future cities. In practice, if the wind speed of 1.5m/s is available in the urban areas in Hong Kong, there would be still more than 50% of people feeling comfortable within the T_{mrt} range of 26.7-42.6℃. The most comfortable T_{mrt} ranges are 17.3-26.7℃ at T_a>26.0 ℃ and 36.4-42.6℃ at T_a≤26.0 ºC, respectively.

4. Conclusions

In this study, we proposed a novel approach to discuss the applicability of UTCI in evaluating the outdoor thermal comfort in Hong Kong and a new index to evaluate the outdoor thermal comfort in respective of the combined sun and wind conditions. To explore the applicability of UTCI, we compared the variations of subjective TSV and UTCI with the changing meteorological and personal parameters, and identified significant factors influencing the subjective TSV and those estimated by UTCI. The analysis conducted in this study were based on the data derived from simultaneous meteorological measurements and questionnaire surveys in subtropical Hong Kong. Therefore, the concept that UTCI needs to be improved in some respects should be cautioned in other climate regions.

Once the factors significantly influencing the subjective TSV have been identified, the new index is subsequently formulated to evaluate outdoor thermal comfort in respective of the combined sun and wind conditions. The advantage of this index is that it’s quite straightforward and helpful in guiding how to properly combine sun and wind conditions in design stage for thermal comfort in urban areas. However, the limitation is that the comfortable combined sun and wind conditions derived in this study are applicable to short-term outdoor exposure. Nevertheless, following conclusions were reached in this study:

1. The discrepancies are found between influences of traditional meteorological and personal factors evaluated by subjective TSV and those estimated by UTCI. Generally based on the survey results, influences of v and T_{mrt} in subjective thermal sensations at higher T_a are more significant than those estimated by UTCI. TSV is not purely influenced by physical effects of v and T_{mrt} but also the subjects' desirability of sun and wind conditions ($D_{S/W}$), which is not considered by UTCI. *RH* is significant estimated by UTCI but found less effective in changing TSV.

2. T_{mrt}, $D_{S/W}$, and v are the top three factors influencing the TSV of people conducting moderate activities, while T_a, T_{mrt}, and v are determining factors estimated by UTCI. Presumably, subjects' adaptive clothes-wearing based on air temperature and their short-term and longitude adaptability to subtropical hot-humid climate in Hong Kong, have made air temperature and relative humidity outdoors less influencing factors than those estimated by UTCI. The applicability of UTCI in hot-humid climate regions like Hong Kong can be improved by calibrating the overestimated influences of T_a and RH and underestimated influences of v and T_{mrt} at higher T_a by UTCI.

3. A new index SWI, combining T_{mrt} and v and reflecting the relative strength of T_{mrt} and v, is defined and applied within the environmental parameter ranges of $12.0 \le T_{mrt} \le 64.0$℃ and $0 < v \le 4.0$m/s. Thermally comfortable combinations of sun and wind conditions where more than 50% of subjects vote comfortable are found at the SWI range of -0.1-0.2 under T_a ranging from 12.0℃ to 36.0℃. Neutral thermal environments with the sun condition slightly stronger than the wind condition (0.1≤SWI≤0.2) and those with the wind condition slightly stronger than the sun condition (-0.3≤SWI≤-0.1) are found most comfortable at $T_a \le 26.0$℃ and $T_a > 26.0$℃, respectively.

As the absolute value of SWI is the same and out of the comfortable range, people exhibit more tolerance to the cooling effects of stronger wind speed than to the heating effects of stronger solar radiation.

4. The v-T_{mrt} diagram, derived from the thermally comfortable combined T_{mrt} and v, proposes three comfort zones, which effectively provides a detailed standard for combining sun and wind conditions for outdoor thermal comfort. The SWI index can be used as a supplemental index to assess the outdoor thermal conditions in the combined sun and wind conditions and provide useful guidance on the urban designs in Hong Kong.

Accordingly, we recommend the improvement of thermal indices like UTCI in the future study, focusing on calibrating their evaluations on influences of meteorological parameters in human thermal responses in hot-humid climate regions, and considering influences of psychological factors. Furthermore, future studies on enriching comfortable combined sun and wind conditions based on more subjects, more outdoor places, more climate regions and longer outdoor exposure time should be conducted under the context of global warming.

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