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The effects of urban microclimate on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate

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ABSTRACT

This study investigated the effects of four important microclimate parameters on outdoor thermal sensation and neutral temperature. A long term (almost 2 years) field investigation was conducted at six typical public spaces in Changsha China, with hot-summer and cold-winter climate. During a single investigation of one day (from 9:00 to 18:00), outdoor air temperature, air humidity, global temperature and wind speed were continuously measured at one measuring point. People visiting the public spaces (near the measuring site) were randomly invited to fill out a questionnaire describing their feelings of thermal comfort and other important psychological factors. Based on the field data (7851 samples), relationship between people's outdoor thermal sensation and the microclimate parameters were quantified. Further, the effect of the microclimate parameters on outdoor thermal sensation and neutral temperatures was analyzed. The results revealed that outdoor microclimate parameters, especially outdoor air temperature, play important roles on outdoor thermal sensation when people stay outdoors. The variation in outdoor microclimate parameters led to the biggest change of outdoor neutral temperature in winter. Seasonal and regional differences in outdoor neutral temperature were found, which reflects different thermal comfort requirements under distinct outdoor microclimate conditions.

1. Introduction

With more and more people choosing outdoor activities in their leisure time, outdoor thermal comfort is attached great importance. Favorable level of outdoor thermal comfort can improve quality of outdoor activities and relieve human hot or cold stress due to adverse weather conditions. A field investigation showed that thermal comfort was the most important factor when people selected an outdoor space [1]. Additionally, comfortable outdoor environment can also improve indoor thermal comfort [2] and is helpful for energy saving. In recent years, urban heat island effect becomes severer with the city development and extreme weather frequently occurs in cities due to the global climate change. Therefore, improving outdoor thermal comfort is especially important for outdoor activities of citizens.

Outdoor microclimate is a significant factor influencing human outdoor thermal comfort. Air temperature, humidity, wind speed and thermal radiation are four important parameters of outdoor microclimate. The outdoor microclimate parameters exert influence on human outdoor thermal comfort with two important ways: thermal sensation and neutral temperature. The existing studies focused on the effect of different microclimate parameters on human thermal sensation in outdoor environment. Givoni et al. found the close relation between outdoor thermal sensation and air temperature or solar radiation [3]. Nikoloupoulou and Lykoudis conducted an analysis on thermal comfort in outdoor urban spaces across different European cities [4]. Their findings also revealed that air temperature and solar radiation were important determinants of outdoor thermal sensation. Stathopoulos et al. confirmed that air temperature played an important role in determining people's overall comfort based on a field investigation in downtown Montreal Canada during 34 days [5]. A recent study (Ruiz and Correa) conducted in Mendoza Argentina showed a high correlation coefficient (>0.9) between outdoor thermal sensation vote and outdoor air temperature [6]. The effect of air humidity and wind on outdoor thermal sensation depended on the range of outdoor air temperature, as revealed by some studies [4,7,8].

The correlation between the outdoor microclimate parameters and human outdoor thermal sensation was quantified with two kinds of models. One is the mechanism model. This kind of model developed the relationship between human thermal sensa-

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Table 1
Outdoor neutral PET and mean air temperature of cold and hot seasons in different cities.

Climate	City	Outdoor mean air temperature (°C)		Outdoor neutral PET (°C)		Reference
		Cold Season (Winter)	Hot Season (Summer)	Cold Season (Winter)	Hot Season (Summer)	
Temperate marine	Kassel, Germany	4.7	21.6	5	21.5	[20]
Subtropics Mediterranean	Tel Aiv, Israel	16	26	22.7	23.9	[12]
Subtropics monsoon	Hongkong, China	17.6	28.4	21	25	[21]
Subtropics monsoon	Taichung, Taiwan	16–21	19–29	23.7	25.6	[22]
Subtropics grassland and desert	Cairo, Egypt	10–20	20–35	21.6–29	22–30.1	[23]

tion and mechanism microclimate indices [9–13]. The mechanism indices, such as Physiologically Equivalent Temperature (PET) [14], Perceived Temperature (PT) [15] and Universal Thermal Climate Index (UTCI) [16], were established based on the mechanism of the heat transfer between human body and outdoor microclimate. Another is the empirical model. The empirical model developed the direct relationship between thermal sensation and multiple (or single) microclimate parameters to quantify the effect of the outdoor microclimate parameters on thermal comfort [3–8,17,18].

Outdoor neutral temperature reflects human requirement of thermal comfort in outdoor environment, which is defined as the outdoor temperature causing people feel neutral (neither cold nor hot). Usually, neutral temperature is a comfortable thermal condition and can be accepted by most people [19]. Some studies obtained outdoor neutral temperatures of different climate areas [12,20–23]. As listed in Table 1, the outdoor neutral PET (NPET) in the cities with hot climate was higher than the cities with cold climate. The difference in the outdoor NPET was bigger especially in cold season. As an example, the winter outdoor NPET can reach 29 °C in Cairo, Egypt (a subtropical city), while it decreased to 5 °C in Kassel, Germany (a temperate city).

There were some limitations in the existing studies. First, the studies for hot-summer and cold-winter climate were few. The effect of the microclimate parameters on outdoor thermal comfort was distinct in different climate conditions and countries. Second, the investigation samples were limited. In most studies, the field investigation was conducted only in a short period (several days or weeks). That means the results can not fully reflect the difference in outdoor thermal comfort caused by the change of season in a whole year. Third, the existing studies did not reveal the effects of the outdoor microclimate parameters on outdoor neutral temperature, which can provide more useful basis for the design of public spaces.

This study aimed to investigate the effects of different microclimate parameters on outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate, based on a long term (almost 2 years) field investigation conducted in various public spaces of a typical city in China.

2. Method

2.1. Study city

Changsha is the capital of Hunan province located in the south-central area of China (28°11′N, 112°58′E), with a climate of hot summer and cold winter. The variation of climate with different seasons in a year is notable (see Section 3.2). During recent years, the development of Changsha is fast, which attracts more and more people (more than 7 million inhabitants). Many outdoor public spaces have been built in the city. The outdoor thermal comfort field investigation was carried out in some important outdoor spaces in Changsha.

2.1.1. Location

Six typical outdoor public spaces were selected as the field investigation locations. People can freely visit these public spaces. As shown in Fig. 1, three public spaces (P1–P3) locate in the downtown and the other spaces (P4–P6) in the old and new campuses of Central South University in Changsha. The role of different physical characteristics on outdoor microclimate was considered for the selection of these locations. Locations P1 and P4 are grass without trees, while P2 and P6 are brick ground with high trees. These four locations are very close to or surrounded (P1) by water body. Locations P3 and P5 are brick ground without trees and far away from water body.

2.1.2. Protocol

The outdoor field investigation was conducted three or four days every week from Mar. 2012 to Dec. 2013, except for some holidays and bad weather (middle/strong rain, snow, extreme hot/cold, etc.) days. During the whole period, the field investigation was conducted on 146 days at the six locations. Among these days, there were 45 sunny days and 87 cloudy days. The distribution of the investigation days in four seasons was: 31 days in spring, 55 days in summer, 34 days in autumn and 26 days in winter.

From 9:00 to 18:00 of each day, only one of the six locations was investigated. All the six locations were visited in turn by the researchers, but in different days during the whole period. There was 1 measuring site for outdoor microclimate parameters in every location. During a single investigation (1 day), air temperature, air humidity and wind speed were continuously measured at the measuring point and automatically recorded per minute. The global temperature was continuously measured and recorded by the researchers every five minutes.

During 9:00–18:00 in each day, people visiting the public spaces (near the measuring site) were randomly invited to fill out a questionnaire reflecting their feelings of thermal comfort and other important factors described in Section 2.1.4. The researchers gave a brief introduction on the questions in the questionnaire to every subject if he accepted the invitation. After he understood all questions, the subject began to fill out the questionnaire. The time when he finished the questionnaire was recorded by the researchers. The number of subjects in every day was not the same, with a max of 180.

2.1.3. Instrumentation

Four important outdoor microclimate parameters were monitored. The air velocity, the temperature and the relative humidity were collected using a multifunctional portable Weather & Environmental Meter (Kestrel 4500, NK Company, USA). The global temperature was measured using a standard black-bulb (D 150 mm, KIMO, FR). The precision of each instrument is listed in Table 2. During the measurement, the outdoor microclimate parameter measuring instruments were placed on two tripods at a height of 1.1 m, as shown in Fig. 1.

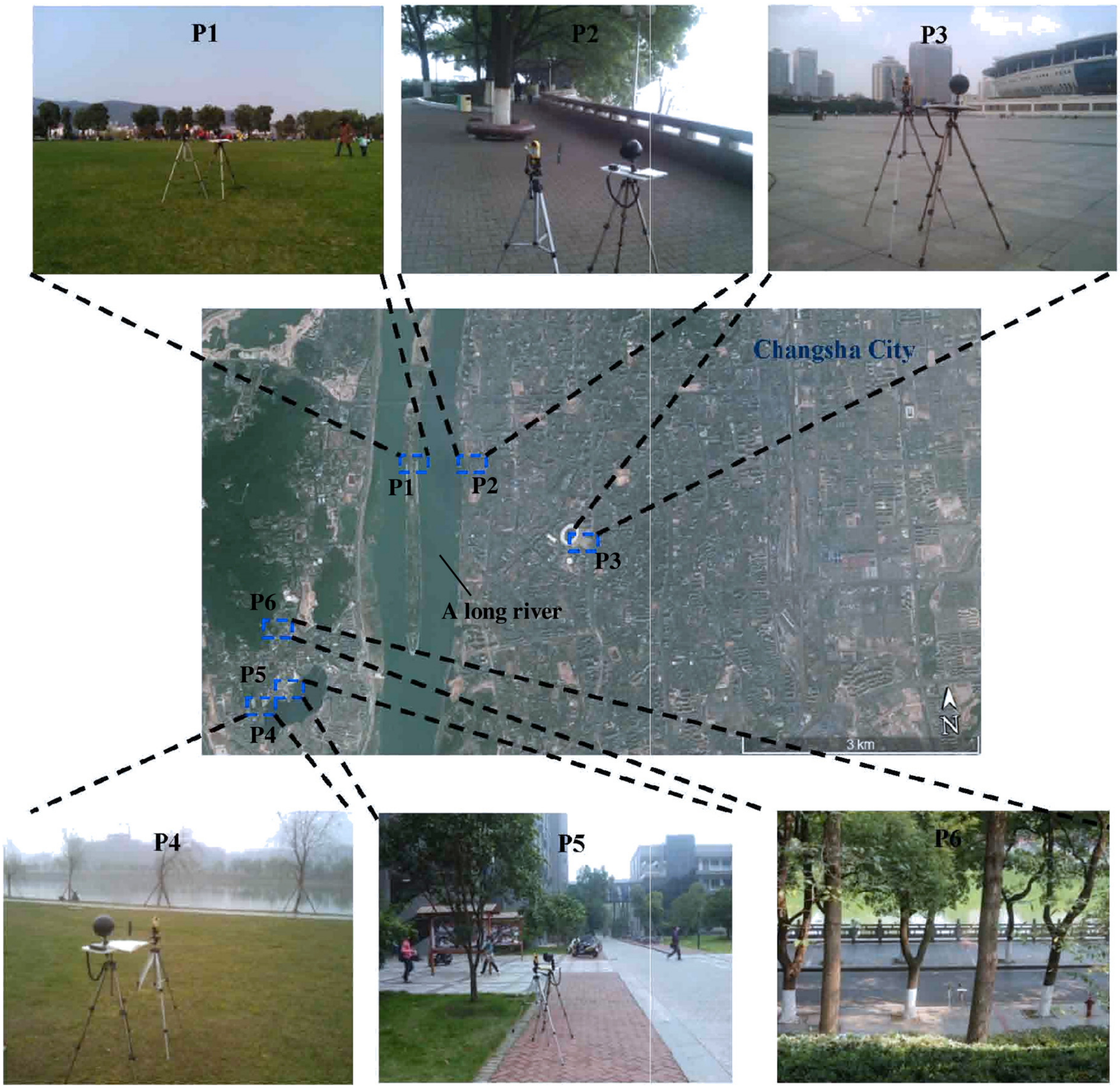

Fig. 1. Six outdoor field investigation locations. P1 is a park at a small island. P2 is a big sidewalk along a river. P3 is a public square. P4 is grassland beside an artificial lake. P5 is a sidewalk between two classroom buildings and P6 is a sidewalk beside an artificial lake.

Table 2
Instruments for the measurement of outdoor microclimate parameters.

Parameter	Instrument	Scale	Precision	Resolution
Global temprerature	Digital thermometer TR102	−100–400 °C	±0.3 °C	0.1 °C
Outdoor air temperature	Kestrel 4500	−29–70 °C	±1.0 °C	0.1 °C
Wind speed	Kestrel 4500	0.4–40 m/s	±0.1 m/s	0.1 m/s
Outdoor relative humidity	Kestrel 4500	5–95%	±3%	0.1%

The difference (T_{ga}) between the outdoor air temperature (T_a) and the global temperature (T_g) reflects the intensity of outdoor thermal radiation, calculated as,

$$T_{ga} = T_g - T_a \tag{1}$$

A bigger value of T_{ga} means a stronger intensity of outdoor thermal radiation. Therefore, the value of T_{ga} can be used to reflect the role of outdoor thermal radiation. At the investigation locations, outdoor thermal radiation mainly included solar radiation and long wave radiation from the surfaces.

2.1.4. Questionnaire

The questionnaire was carefully designed to obtain the following main information:

(1) Personal information, including age, gender, height, body weight, birthplace, profession, education, the period for living in Changsha and the average time spent in outdoor in daily life, etc.
(2) Past experience, including previous environment (air conditioning/naturally ventilated/outdoor) and activity levels before arriving here.
(3) Subjective responses to outdoor microclimate, which focused on various responses to outdoor temperature, humidity, wind

speed and solar radiation. In this study, only the thermal sensation response was analyzed. People's thermal sensation was evaluated using a 9-points scale: −4 (very cold), −3 (cold), −2 (cool), −1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm), +3 (hot), and +4 (very hot) [12], which is an extension of ASHARE 7-points scale, considering the larger variation in outdoor climate conditions.
(4) Current clothing and activity levels. The subjects were asked to record the combination of their clothing in order from underwear to outerwear. A fairly detailed clothing garment list was provided for option [24]. The subjects were also asked to describe current activity and the corresponding duration.
(5) Related psychological factors. For example, thermal expectation and preference before visiting the location, current mood, the reason to coming to the location and the evaluation on the building and sight in the location, etc.

The questionnaire was written in Chinese. The subjects spent about five minutes in completing the questionnaire after they understood every question.

2.2. Statistical analysis

The effect of outdoor microclimate parameters on human outdoor thermal comfort was analyzed using statistical analysis methods.

(1) Multi-factor analysis of variance was applied for the test of significance of the effect of each microclimate parameter on outdoor thermal sensation, considering the synergistic effect of the other microclimate parameters.
(2) Multiple linear regression analysis was used to establish the models to quantify the relationship between multiple outdoor microclimate parameters and thermal sensation.

To evaluate a regression equation, the determination coefficient R^2 was used to indicate the goodness of fit, and the level of significance was set at sig. ($p < 0.05$).

3. Results and analysis

3.1. Outdoor field investigation samples

A total of 8586 samples (questionnaires) were collected. First the questionnaires with deficient or abnormal data were excluded. Then outlier detection was performed based on the thermal sensation votes and the corresponding PET values. The values of PET were calculated with the RayMan program [25]. For each level of thermal sensation vote, the samples with PET falling outside 1.5 IQR (interquartile range) of 25th and 75th percentiles were evaluated as outliers and deleted. Finally, 7851 samples were used for further analysis. The numbers (percentage) of the samples in each season were 2282 (29%) in spring, 2185 (28%) in summer, 1708 (22%) in autumn and 1676 (21%) in winter.

Among all the subjects interviewed by the researcher, males took a proportion of 57% (4722) and young people (<30) have a proportion of 94% (7618).

3.2. Outdoor microclimate parameters and thermal sensation votes

The outdoor microclimate parameters and the thermal sensation votes obtained in the outdoor field investigation provided sufficient raw data for the present study. First, for the air temperature, the air humidity and the wind speed, the mean values during 5 min were calculated based on the raw data. The global temperatures were the recorded values every 5 min. And then, the corresponding values at the time when the questionnaires were filled out were applied for the analysis of relationship between microclimate parameters and thermal sensation.

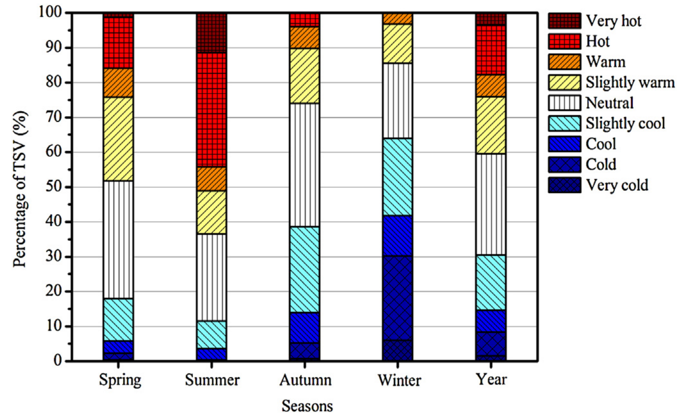

Fig. 2. The distribution of the thermal sensation votes (TSV) in different seasons and whole period (Year).

The statistical result of the outdoor microclimate parameters is listed in Table 3. The mean air temperature in summer was 30.2 °C, while it decreased to 8.6 °C in winter. In the transition seasons (spring and autumn), the outdoor air temperature had a mean of about 20 °C. The variation in the global temperature with seasons was similar to that in the air temperature. The mean air relative humidity and the mean wind speed in each season were approximately 60% and 0.9 m/s, respectively.

The thermal sensation of the subjects at the six locations is depicted in Fig. 2. The distribution of the thermal sensation votes in each season was different. In summer, more than 60% of the total subjects voted the thermal sensation from slightly warm to very hot, with the highest proportion (>30%) of hot votes. The distribution of thermal sensation votes reversed in winter: more than 60% of the votes were lower than 0 (neutral) and the cold votes possessed the highest proportion (about 25%). In the transition seasons, the thermal sensation votes were centered on slightly warm, neutral and slightly cool sensation, among which the neutral votes had the highest proportion (about 26%).

3.3. Relative contribution of different microclimate parameters to outdoor thermal sensation

All the microclimate parameters influence outdoor thermal sensation together. Therefore, multifactor analysis of variance was performed to evaluate the individual effect of outdoor air temperature, air humidity, thermal radiation and wind speed. The results for the whole period and seasons were listed in Table 4. It can be known that every outdoor microclimate parameter exerted significant effect on the thermal sensation ($p < 0.05$).

In order to evaluate relative contribution to the thermal sensation, a contribution factor was defined as the proportion of the Square for each microclimate parameter to the total sum of Squares (see Table 4). The values of the contribution factor (percentage) were shown in Fig. 3. Air temperature made the biggest contribution (>40%) to the thermal sensation in spring, summer and autumn, and possessed the second place of the contribution in winter. The contribution of thermal radiation was the highest (almost 50%) in winter, while lowest (<10%) in spring. The situation of the contribution of each outdoor microclimate parameter during the whole period (Year) was similar with those in summer and autumn.

Table 3
The statistical result of outdoor microclimate parameters during the field investigation.

	Outdoor air temperature (°C)				Outdoor air relative humidity (%)				Outdoor wind speed (m/s)				Outdoor global temperature (°C)			
	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD
Spring	10.1	34.7	21.3	4.9	16.1	94.8	57.6	16.0	0	2.7	0.7	0.6	11.4	47.8	27.1	7.8
Summer	18.7	39.8	30.2	4.4	28.4	89.8	59.9	12.8	0	3.7	0.9	0.7	18.8	57.0	35.8	7.7
Autumn	5.9	33.5	18	5.4	27.3	91	61.7	15.3	0	3.5	0.9	0.6	6.8	43.0	22.0	8.0
Winter	1.9	17.4	8.3	3.4	30	85.5	66.0	13.1	0	3.5	0.9	0.6	1.9	30.7	11.3.	6.0
Year	1.9	39.8	22.2	9.1	16.1	94.8	60.6	14.4	0	4.3	0.9	0.7	1.9	57.0	25.9	11.5

SD means Standard Deviation. Year means the whole investigation period.

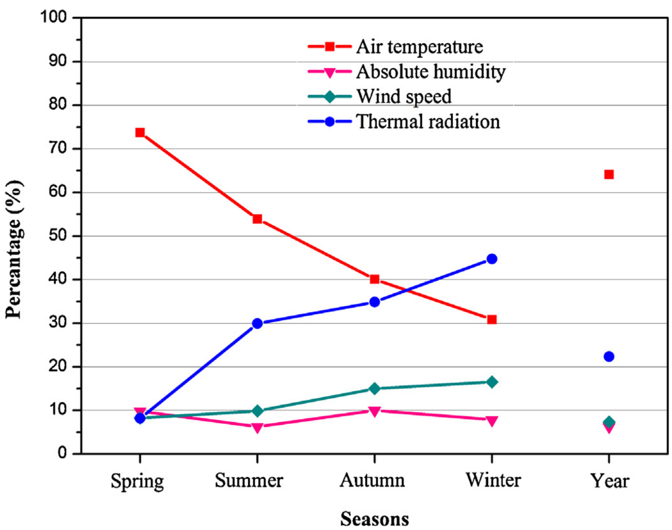

Fig. 3. The relative contribution of the outdoor microclimate parameters to human outdoor thermal sensation in different seasons and whole period (Year). Solar radiation was estimated by the difference (T_{ga}) between the outdoor air temperature and the global temperature.

3.4. Models for the relationship between the microclimate parameters on outdoor thermal sensation

To reduce the negative effect of the individual difference in samples on the goodness of fit, the data (thermal sensation votes, PET and outdoor microclimate parameters) in 1 h were combined and the average was calculated, considering that the change of the outdoor microclimate parameters was small in 1 h [26]. Based on the hourly average data (682 sets of samples), the empirical model and the mechanism model were established.

3.4.1. The empirical model

The thermal sensation votes and four outdoor microclimate parameters were correlated directly. The equations for the whole period (Year) and each season were listed as follows.

$$\text{Year}\quad TSV = 0.146T_a - 0.007A_h - 0.308W_s + 0.097T_{ga} - 2.819 \quad R^2 = 0.794 \quad p < 0.01 \tag{2.a}$$

$$\text{Spring}\quad TSV = 0.172T_a - 0.041A_h - 0.191W_s + 0.042T_{ga} - 2.779 \quad R^2 = 0.630 \quad p < 0.01 \tag{2.b}$$

$$\text{Summer}\quad TSV = 0.236T_a + 0.015A_h - 0.325W_s + 0.091T_{ga} - 5.886 \quad R^2 = 0.777 \quad p < 0.01 \tag{2.c}$$

$$\text{Autumn}\quad TSV = 0.112T_a - 0.011A_h - 0.373W_s + 0.110T_{ga} - 2.297 \quad R^2 = 0.608 \quad p < 0.01 \tag{2.d}$$

$$\text{Winter}\quad TSV = 0.121T_a + 0.102A_h - 0.464W_s + 0.111T_{ga} - 2.882 \quad R^2 = 0.718 \quad p < 0.01 \tag{2.e}$$

where *TSV* is outdoor thermal sensation vote, T_a, A_h, W_s and T_{ga} means outdoor air temperature, absolute humidity, wind speed and the difference between the outdoor air temperature and the global temperature, respectively.

3.4.2. The mechanism model

The index of PET was used to develop the mechanism model. The relationship between the thermal sensation votes and the values of PET was established as follows.

$$\text{Year}\quad TSV = 0.130PET - 2.422 \quad R^2 = 0.790 \quad p < 0.01 \tag{3.a}$$

$$\text{Spring}\quad TSV = 0.131PET - 2.296 \quad R^2 = 0.585 \quad p < 0.01 \tag{3.b}$$

$$\text{Summer}\quad TSV = 0.188PET - 4.386 \quad R^2 = 0.778 \quad p < 0.01 \tag{3.c}$$

$$\text{Autumn}\quad TSV = 0.112PET - 2.232 \quad R^2 = 0.521 \quad p < 0.01 \tag{3.d}$$

$$\text{Winter}\quad TSV = 0.163PET - 2.431 \quad R^2 = 0.663 \quad p < 0.01 \tag{3.e}$$

3.5. Outdoor neutral air temperature and neutral PET

3.5.1. Outdoor neutral air temperature

Outdoor neutral air temperature (NAT) is determined as the outdoor air temperature at which the mean thermal sensation vote equals 0 "(neutral"). According to Eq. (2.a), (2.b), (2.c), (2.d) and (2.e), the outdoor air absolute humidity, wind speed and thermal radiation can influence the outdoor NAT. In order to remove the effect of the three microclimate parameters, a standard thermal condition was assumed as follows.

(1) Outdoor air absolute humidity was set to 8.87 mg/L (approximately equivalent to a water vapour pressure of 12 hPa or relative humidity of 51% at 20 °C);
(2) Outdoor wind speed was set to 0.1 m/s;
(3) Outdoor air temperature equals global temperature (T_{ga} = 0, no thermal radiation).

The standard thermal condition was the same as that used in the determination of PET [14]. Based on the assumed standard thermal condition, the outdoor NAT was calculated with Eq. (2.a), (2.b), (2.c), (2.d) and (2.e). The result was shown in Fig. 4. The outdoor NAT reached the highest value (24.5 °C) in summer and the lowest (16.7 °C) in winter. The outdoor NAT was higher in autumn (21.7 °C) than in spring (18.3 °C).

When the real thermal condition deviates from the standard condition, the outdoor NAT will change according to the deviation degree. Based on the empirical model, the variation in NAT caused

Table 4
Multifactor analysis of variance for the contribution of outdoor microclimate parameters to human outdoor thermal sensation.

	Spring SS	DF	MS	F	sig.	Summer SS	DF	MS	F	sig.
CM	2078.6	84	24.7	18.4	0.00	3237.6	98	33.0	21.0	0.00
INT	14.0	1	14	10.4	0.00	111.5	1	111.5	71.0	0.00
Ta	803.1	20	40.2	29.8	0.00	606.4	23	26.4	16.8	0.00
Ah	107.1	13	8.2	6.112	0.00	70.3	17	4.1	2.6	0.00
Ws	89.8	34	2.6	1.960	0.00	111.0	35	3.2	2.0	0.00
Tga	89.5	17	5.3	3.9	0.00	336.6	23	14.6	9.3	0.00
ERR	3072.9	2280	1.348			3129.7	1994	1.6		
TOT	6108.0	2365				11072.0	2093			
CT	5151.5	2364				6367.2	2092			

	Autumn SS	DF	MS	F	sig.	Winter SS	DF	MS	F	sig.	Year SS	DF	MS	F	sig.
CM	922.5	80	11.5	8.4	0.00	1485.6	66	22.5	13.0	0.00	14676.1	121	121.3	78.1	0.00
INT	0.1	1	0.1	0.1	0.80	35.8	1	35.8	20.7	0.00	17.7	1	17.7	11.4	0.00
Ta	221.5	21	10.5	7.7	0.00	214.6	15	14.3	8.3	0.00	2815.8	37	76.1	49.0	0.00
Ah	55.4	13	4.3	3.1	0.00	54.5	7	7.8	4.5	0.00	274.4	23	11.9	7.7	0.00
Ws	83.0	28	2.9	2.2	0.00	114.9	25	4.6	2.6	0.00	320.5	38	8.4	5.4	0.00
Tga	192.9	18	10.7	7.8	0.00	311.3	19	16.4	9.5	0.00	980.9	23	42.6	27.5	0.00
ERR	2239.5	1637	1.4			2834.9	1639	1.7			12050.0	7760	1.6		
TOT	3218.0	1718				6950.0	1706				27348.0	7882			
CT	3162.1	1717				4320.5	1705				26726.1	7881			

Ta means outdoor air temperature, Ah outdoor air absolute humidity, Ws outdoor wind speed and Tga the difference between the outdoor air temperature and the global temperature.
SS, DF, MS,CM, INT, ERR, TOT and CT mean sum of squares, means degree of freedom, mean square, corrected model, intercept, error, total and corrected total, respectively.
F is a statistical variable for F test. sig. means the value of P.
Year means the whole investigation period.

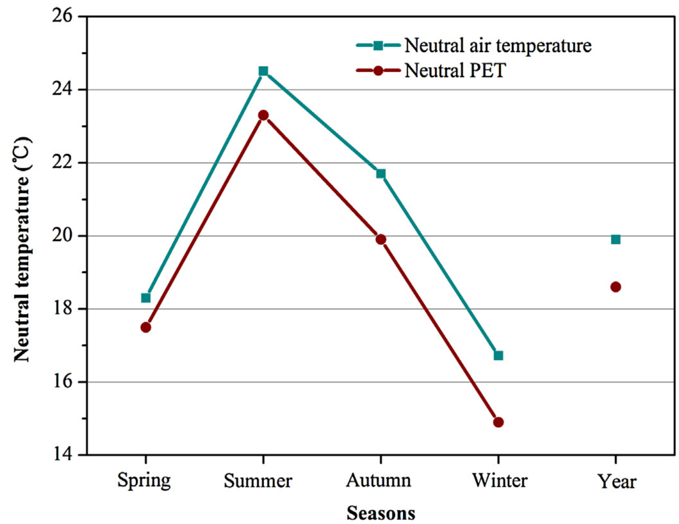

Fig. 4. The outdoor neutral air temperature and PET in different seasons and whole period (Year).

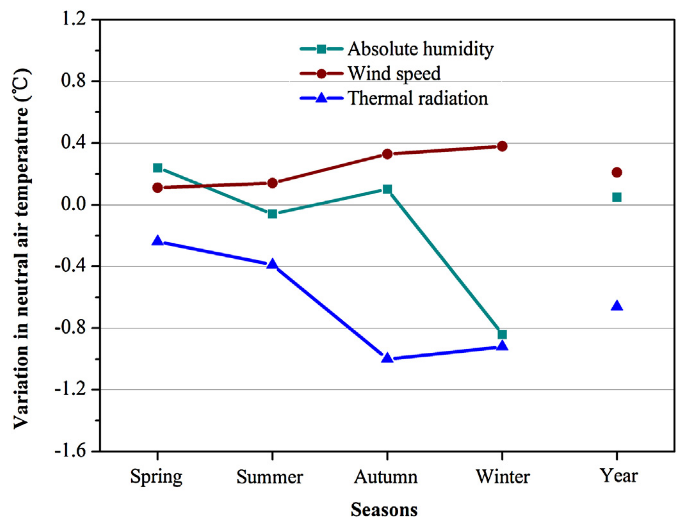

Fig. 5. Variation in outdoor neutral air temperature caused by increase of the outdoor microclimate parameters in different seasons and whole period (Year). Thermal radiation was estimated by the difference (T_{ga}) between the outdoor air temperature and the global temperature. The increase in outdoor absolute humidity, wind speed and solar radiation (T_{ga}) were 1 mg/L, 0.1 m/s and 1 °C, respectively.

by the change of an outdoor microclimate parameter can be determined with the ratio of the regression coefficient for the parameter to that for the outdoor air temperature. The result was illustrated in Fig. 5. It can be seen that the change of the outdoor NAT, due to the rise in outdoor thermal radiation and wind speed, increased with the season changing from spring to winter.

3.5.2. Outdoor neutral PET

Outdoor neutral PET (NPET) was calculated as the PET at which the mean thermal sensation vote was "neutral". The calculation of the outdoor NPET was done based on the mechanism model (Eq. (3.a) and (3.b)). The result was shown in Fig. 4. Seasonal difference in the outdoor NPET was found. In Changsha, the outdoor NPET reached the highest value (23.3 °C) in summer and the lowest value (14.9 °C) in winter, with a temperature difference of 8.4 °C.

A comparison of outdoor NPET range between three climate regions was shown in Table 5. The outdoor NPET range was defined as the PET range causing mean thermal sensation vote between −0.5 and +0.5. Here, the outdoor NPET range was determined based

Table 5
PET ranges and outdoor thermal sensation levels for different cities.

Scale	Thermal sensation	PET range for Changsha (°C)	PET range for Tel Aviv[a] (°C)	PET range for Taiwan[b] (°C)
	Very cold			
−3.5		−8	8	14
	Cold			
−2.5		−1	12	18
	Cool			
−1.5		7	15	22
	Slightly cool			
−0.5		15	19	26
	Neutral			
+0.5		22	26	30
	Slightly warm			
+1.5		30	28	34
	Warm			
+2.5		38	34	38
	Hot			
+3.5		46	40	42
	Very Hot			

[a] Cohen et al. [12].
[b] Lin and Matzarakis [11].

on Eq. (3.a). The boundary of the NPET range (15–22 °C) in Changsha was lower than in Tel Aviv and Taiwan.

4. Discussion

The present results revealed the effects of the outdoor microclimate parameters on human outdoor thermal sensation and neutral temperature in hot-summer and clod winter climate. As indicated by the empirical model, the increase in outdoor air temperature and thermal radiation led to the rise of outdoor thermal sensation, while wind speed had opposite effect. This can be explained by the different roles of these microclimate parameters on human body heat balance [19]. Seasonal difference was found in the effect of the outdoor absolute humidity on outdoor thermal sensation. The increase in outdoor air absolute humidity made people feel warmer in summer and winter, while feel cooler in transition seasons. The possible reason was that human body was not sensitive to the variation in air humidity [4,19,27], and the effect of air humidity on thermal sensation depends largely on the outdoor air temperature.

Outdoor air temperature was the most important microclimate parameter to outdoor thermal sensation, and the second important factor was outdoor thermal radiation, as reflected by the bigger relative contribution illustrated by Fig. 3. The result confirms previous findings [4–6]. It is interesting to observe that, with the season changing from spring to winter, the relative contribution of outdoor air temperature decreased, while that of outdoor thermal radiation increased. Especially in winter, outdoor thermal radiation contributed more to outdoor thermal sensation than outdoor air temperature. In winter, outdoor air temperature was always low (Table 3) and most thermal sensation votes were on the cold side (Fig. 2). However, outdoor thermal radiation (mainly solar radiation) can directly make people feel warm in cold climate condition, which exerts more important effect on outdoor thermal sensation.

The variation in outdoor thermal sensation under the influence of the microclimate parameters can cause the change of outdoor neutral temperature. The elevation of outdoor wind speed led to the increase in the outdoor NAT (positive value of the NAT variation rate), while opposite effect on the outdoor NAT was caused by outdoor thermal radiation (negative value of the NAT variation rate). The increase in outdoor absolute humidity elevated the outdoor NAT in spring and autumn, while reduced the outdoor NAT in summer and winter. The three outdoor microclimate parameters exerted stronger effect on the outdoor NAT in winter (or autumn) as indicated by higher NAT variation rate (Fig. 5). That is to say, the change of outdoor air humidity, thermal radiation and wind speed can cause bigger variation in outdoor neutral temperature in winter (or autumn) than in other seasons. This might be related to the seasonal variation in relative contribution of the microclimate parameters to outdoor thermal sensation (Fig. 3).

Regional difference in the outdoor NPET was found. Compared with the subtropical cities listed in Table 1, Changsha possessed lower outdoor NPET in summer and winter, and bigger NPET difference between the two seasons. As reflected by Table 5, the range of the outdoor NPET in Changsha was also bigger than those in Tel Aviv and Taiwan. The regional difference can be related to the distinct climate conditions. Among these subtropical cities, only Changsha has a hot-summer and cold-winter climate, with the biggest difference (21.9 °C) in outdoor mean air temperature between summer and winter. Bigger seasonal difference in the outdoor NPET and wider outdoor NPET range indicate that people living in Changsha adapted to the seasonal variation in the outdoor climate very well.

As mentioned before, both the empirical model and the mechanism model are widely used in the outdoor thermal comfort researches. However, no studies made a direct comparison between the two models. Fig. 4 reflects the difference in outdoor neutral temperatures determined with the two models. The outdoor NAT was higher than the outdoor NPET in the whole period and each season. The relationship was quantified with following regression equation.

$$NPET = 1.015NAT - 1.6882 R^2 = 0.981 \quad (4)$$

Both outdoor neutral temperatures were calculated based on the same assumed thermal environment conditions. The difference between the outdoor NAT and NPET was mainly caused by the different microclimate indexes, air temperature and PET. The change of outdoor air temperature can induce the occurrence of thermoregulation and psychological adaption (i.e. thermal expectation). Therefore, outdoor air temperature in the empirical model reflects the effect on body heat balance and the psychological adaption together. PET in the mechanism model is determined based on the synergistic effect of all four outdoor microclimate parameters on body heat balance (thermoregulation) [14] and has no relationship with the psychological adaption. The complicated calculation method of PET can also contribute to the difference.

Briefly, the results of this study indicate that outdoor microclimate parameters exert important influence on human thermal comfort in urban public spaces under hot-summer and cold-winter climate. The influence should be carefully considered in urban planning, as pointed out by some previous studies [13,28,29]. Different from the existing studies, the present work quantified the relative contribution of different microclimate parameters to outdoor thermal sensation and revealed their effect on outdoor neutral temperature in each season. These are helpful for designing an urban public space to meet human thermal comfort requirement in different seasons, by applying suitable surface materials, water body, plants, sunshade, etc.

5. Conclusion

The effects of the outdoor microclimate parameters on human outdoor thermal sensation and neutral temperature in hot-summer and cold-winter climate was analyzed. Following conclusions were obtained.

(1) Outdoor microclimate parameters play important role on thermal comfort when people stay outdoors. Outdoor air temperature was the most important microclimate parameter for outdoor thermal sensation.
(2) The relative contribution of outdoor air temperature to outdoor thermal sensation decreased gradually, with the season changing from spring to winter. For outdoor thermal radiation, the trend of the contribution to outdoor thermal sensation reversed.
(3) The elevation of outdoor wind speed led to the increase in the outdoor NAT, while opposite effect on the outdoor NAT was caused by the increase in outdoor thermal radiation. The variation in outdoor absolute humidity and wind speed led to the biggest change rate of the outdoor NAT in winter.
(4) There were seasonal and regional differences in the outdoor NPET, which reflected different thermal comfort requirements under distinct outdoor microclimate conditions.

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