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Studies of Outdoor Thermal Comfort in Northern China

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Abstract

Outdoor spaces play important roles in daily lives, and the use of these spaces is determined largely by outdoor thermal comfort. Few studies have been conducted on outdoor thermal comfort in northern China. Using microclimatic monitoring and subject interviews at a park in Tianjin, China, this investigation studied outdoor thermal comfort under different climate conditions. Although outdoor thermal environment varied greatly with air temperature from -5.0 to 34.5°C, 83.3% of respondents consider it "acceptable". Preferences in solar radiation, wind speed, and relative humidity were related to air temperature. The higher the air temperature was, the higher the wind speed and the lower the solar radiation and relative humidity desired by the occupants, and vice versa. The data were also used to evaluate three indices. The Universal Thermal Climate Index (UTCI) satisfactorily predicted outdoor thermal comfort, while the Predicted Mean Vote (PMV) overestimated it. The neutral Physiological Equivalent Temperature (PET) range found in this study was 11-24°C, which was lower than the ranges in Europe and Taiwan. Our study indicated that residents of Tianjin were more adapted to cold environment.

Keywords

Outdoor spaces; thermal comfort; cold climate; thermal sensation; thermal index

1. Introduction

Over half of the world's population lives in cities [1]. Various outdoor or semi-outdoor spaces, including city parks, squares, pedestrian streets, residential areas, sports stadiums, etc., provide places for citizens to exercise and socialize. In addition, because recreational activities of considerable commercial value are conducted outdoors [2], the quality of these spaces directly affects the livability and vitality of a city. In addition, revitalizing outdoor spaces will lead to energy saving inside buildings. As people spend more time in outdoor spaces, the usage of air conditioners and other electronic equipment will be reduced. Among the many factors that influence outdoor space quality, outdoor microclimate or the concomitant outdoor thermal comfort is important [3]. Several studies investigated the correlations between thermal comfort and occupancy in outdoor spaces [4-9], most of them have identified that a strong correlation did exist.

Since the start of the new millennium, outdoor thermal comfort has received great attention. A growing number of thermal comfort studies have been conducted for various outdoor spaces in different climate regions. For example, Nikolopoulou et al. [10] investigated a wide variety of locations in seven cities across five European countries. Their findings confirmed a strong relationship between microclimate and comfort conditions. Spagnolo et al. [2] studied various outdoor and semi-outdoor locations in Sydney. They found that the outdoor environment had a wider "comfort zone" than the indoor environment. Lin [11] studied a public square in Taiwan, and the results showed that the thermal comfort range and neutral temperature for subjects in Taiwan were higher than those for people in a temperate region. Mahmoud [12] investigated a park in Cairo and observed changes in comfort level among different landscape zones. Lai et al. [13] surveyed a housing community in Wuhan and proposed a Thermal Sensation Vote (TSV) model and a space usage rate model for this area. These studies have provided valuable knowledge concerning the effect of microclimate on outdoor thermal comfort and space usage. Furthermore, the studies show differences in outdoor thermal comfort among various climatic zones. For instance, Kántor et al. [14] found that the neutral Physiological Equivalent Temperature (PET) in Taiwan differed drastically, by 9 K, from that in Szeged, Hungry. These studies suggest the need for additional field surveys of subjective human perception in the outdoor context [15]. The existing surveys were conducted primarily in temperate or tropical climate regions where the winter is mild or warm. Although Stathopoulos et al. [16] investigated thermal comfort in a cold climate (Montreal, Canada), their survey was conducted at noontime in the spring and fall seasons, when the air temperature was not very low. Because no studies have been performed in the cold climate region of northern China, where the temperature can easily fall below 0^{o}C in winter, a better understanding of the outdoor thermal comfort in this region constitutes our main research objective.

In previous studies, various indices have been used to describe and evaluate the results. For example, Berkovic et al. [17] applied the Predicted Mean Vote (PMV) to investigate thermal comfort in courtyards in a hot, arid climate. Lin [11], Ng et al. [18], Kántor et al. [19], and Kruger et al. [20] used PET to determine the neutral temperature in the climate regions they studied. Because of the different thermal indices and thermal assessment procedures applied in these studies, the results may not be comparable. Meanwhile, the Universal Thermal Climate Index (UTCI) was developed by 45 scientists with multidisciplinary backgrounds from 23 countries in order to standardize applications across major fields of human biometeorology [21]. In addition to thermal indices, many studies of outdoor thermal comfort have used evaluation criteria developed for indoor thermal comfort. For example, Kariminia et al. [22] assessed the thermally acceptable range of an outdoor space by using the middle three thermal sensation votes (-1, 0, 1) as suggested by De Dear and Fountain [23] for an indoor study. However, because outdoor spaces have a broader thermal variation, direct use of an indoor thermal comfort model for outdoor spaces may not be appropriate. The broad thermal variation in outdoor settings also underscores the importance of other meteorological parameters such as radiation, wind and humidity. Since no single thermal environmental factor can explain the entire picture of outdoor thermal comfort [11], it is important to identify relative importance of different parameters. For example, a study in Taiwan [24] revealed that air temperature and mean radiant temperature (T_{mrt}) are most significantly related to outdoor thermal perceptions. In addition to objective weather parameters, subjective human parameters are significant. For instance, age may be a crucial factor because the physiological and psychological characteristics of different age groups may affect their outdoor thermal perception and comfort levels. Therefore, it is important to understand these differences.

This paper reports the findings of a nearly year-long study of outdoor thermal comfort in a cold climate in China, and our use of the data to evaluate the applicability of different thermal indices, including PMV, PET and UTCI, to an outdoor environment in this region.

2. Method

2.1 The site

Our investigation was conducted at Fenghu Park in Tianjin (near Beijing), in northern China. The park is located in the center of Tianjin and has an area of 6600 m^2, as shown in Figure 1. It encompasses a variety of micro-environments, including two kiosks that provide abundant shade, an open square that receives direct sunlight, and a walking path that connects these micro-environments and is bordered by a significant amount of vegetation. The variety of micro-environments enables interactive physical adaptation [25]. In other words, the occupants can interact with the environment to improve their thermal comfort. People from the surrounding communities typically come to Fenghu Park to exercise, relax, chat, or attend to children.

Fig. 1. Location and layout of the park investigated.

2.2 Field survey

Outdoor microclimate has a direct impact on the thermal comfort of occupants and consequently affects their outdoor activity level. This investigation conducted 11 field surveys that involved microclimatic monitoring, questionnaires, and activity recording between 10:00 and 16:00. These surveys were completed between March 13, 2012, and January 8, 2013. Our study defined the period from November to March as the "cold season" with an average air temperature below 10°C; the period from June to August as the "hot season" with an average air temperature above 20°C; and the remaining months as "shoulder seasons." The 11 field surveys covered the three typical seasons (four surveys for the cold season, four for the shoulder seasons, and three for the hot season).

For microclimatic monitoring, two HOBO micro weather stations were deployed in an open space and under a pavilion to record the air temperature (T_a), relative humidity (RH), wind speed (V_a), and global solar radiation (G) every 10 minutes at a height of 2 m above the ground. The globe temperature, T_g, was manually recorded every 30 minutes with the use of two 70 mm global thermometers. Table 1 shows the specifications of the sensors used to measure the micrometeorological parameters in Fenghu Park. All instruments complied with ISO 7726 [26].

Table 1.Sensors used for measurement of micrometeorological parameters.

Parameter	Sensor	Range	Accuracy
Air temperature	S-THB-M002	-40-75°C	±0.2K at 20°C
Relative humidity	S-THB-M002	0-100%	±3%
Wind speed	S-WSET-A	0-45m/s	±1.1m/s
Global radiation	S-LIB-M003	0-1280W/m^2	±10 W/m^2 or ±5%
Globe temperature	SPA 150	-50-250°C	±0.3 K

The mean radiant temperature, T_{mrt}, is defined as the uniform surrounding temperature in an imaginary enclosure in which the radiant heat transfer from a human body to the enclosure surfaces is equal to the heat transfer to the surfaces of an actual enclosure with non-uniform temperatures [27]. Calculation of T_{mrt} was performed according to the ISO 7726 standard, namely:

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.10 \times 10^8 V_a^{0.6}}{\varepsilon D^{0.4}} (T_g - T_a)] \right]^{\frac{1}{4}} - 273 \qquad (1)$$

where D is globe diameter (= 0.07 m in this study) and ε is emissivity (= 0.95 for a black globe).

Figure 2 shows the questionnaire used to collect subjective data in this investigation. The first part of the questionnaire recorded the personal information, activity level, and clothing level of the subjects. The second section collected data related to their thermal comfort and their preference votes (PV) in regard to the weather parameters. Thermal sensation was rated on the ASHRAE seven-point scale for thermal sensation votes. Overall comfort was rated on a three-point scale: uncomfortable, acceptable, and comfortable corresponding to -1, 0, 1 respectively. The four preferred climate parameters, air temperature, global solar radiation, wind speed, and relative humidity, were rated on a three-point scale. A total of 1565 effective questionnaires (525, 601, and 439 for the cold, shoulder, and hot seasons, respectively) were collected in this study.

Outdoor Thermal Comfort Questionnaire

Date: __/__/__ Time:__:__ Location:

Gender: ①Male/②Female Age:

Current occupation or occupation before retirement:

Your current activity:

①Exercising (Light) ②Exercising (Medium) ③Exercising (Heavy) ④Chatting (Standing) ⑤Chatting (Seated) ⑥Strolling ⑦Resting ⑧Attending to Children

What are you wearing right now?

①T-Shirt (Short Sleeves), ②T-Shirt (Long Sleeves), ③Shorts OR Short Skirt, ④Long Pants OR Long Skirt, ⑤Vest, ⑥Sport Skirt, ⑦ Jacket

If you are wearing other clothing, please specify:

Please describe your current thermal sensation:

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	1	2	3

What are your preferences in regard to the following meteorological parameters?

Temperature	Higher	Unchanged	Lower
Wind Speed	Stronger	Unchanged	Weaker
Humidity	Damper	Unchanged	Drier
Solar Radiation	Stronger	Unchanged	Weaker

Please describe your overall comfort level:

Uncomfortable	Acceptable	Comfortable
-1	0	1

Fig. 2. Thermal comfort questionnaire used in this study.

2.3 Thermal comfort indices

This investigation compared several different thermal comfort indices: Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI).

2.3.1 Predicted Mean Vote (PMV)

PMV is a thermal index developed by Fanger [28] on the basis of test data for 1565 subjects in an indoor setting. PMV predicts the mean value of the thermal sensation vote of a large group of people using four weather parameters: air temperature, radiant temperature, air speed, and humidity, as well as two human parameters: clothing level and metabolic rate. As with the thermal sensation vote, PMV is rated on a seven-point scale (-3 = cold, -2 = cool, -1 = slightly cool, 0 = neutral, 1 = slightly warm, 2 = warm, and 3 = hot).

2.3.2 Physiological Equivalent Temperature (PET)

The PET index takes into account all the basic thermoregulatory processes [29]. It is based on a thermo-physiological heat balance model known as the Munich energy balance model for individuals (the MEMI model) [30]. PET is defined using the concept of equivalent temperature: it is the air temperature of a typical indoor room generating the same core and skin temperature as the actual complex outdoor conditions. In this typical room, there is no radiation ($T_{mrt}=T_a$), the air is calm (< 0.1 m/s), and the vapor pressure is 1200 Pa (50% relative humidity at 20^oC). Thus, PET enables a layperson to compare the integrated effects of complex thermal conditions outdoors with his or her own experience indoors. In this study, PET was calculated using RayMan software [31, 32].

2.3.3 Universal Thermal Climate Index (UTCI)

UTCI is expressed as the equivalent ambient temperature of a reference environment that causes the same physiological response of a reference person as would the actual environment [33]. It is based on the Fiala multi-node model [34] of human thermal regulation in combination with an adaptive clothing model. In the clothing model, static clothing insulation is adjusted according to the ambient air temperature, taking into consideration the seasonal clothing habits of Europeans. It is claimed that UTCI is appropriate for thermal assessments in all climates and seasons, and on any scale [21]. In this study, UTCI was calculated by a program provided on the www.utci.org website. Air temperature, mean radiant temperature, relative humidity, and wind speed at a height of 10 m above the ground are required for calculation of UTCI. Wind speed was actually measured at a height of 2 m above the ground and then corrected by the following equation, as suggested in the ASHRAE handbook [27]:

$$V_{a10} = V_{a2} \left(\frac{z}{z'}\right)^{\alpha} \qquad (2)$$

where α is the mean speed exponent, set to 0.33 for city-center areas; V_{a2} the wind speed measured by the anemometers used in our study (m/s); V_{a10} the wind speed at a height of 10 m above the ground (m/s); z the distance from the ground (10 m in this case); and z' the height of the anemometers installed above the ground (2 m in our study). The data collected in the survey provided information for analyzing outdoor thermal comfort in northern China as well as assessing the thermal indices. The following section describes the results.

3. Results

This section first presents the weather conditions that were measured, since they were essential factors in outdoor thermal comfort. Next, thermal comfort is analyzed in detail with respect to weather parameters and age groups in different seasons. Finally, three indices, PMV, PET, and UTCI, were assessed by combining the data from objective microclimatic monitoring and the subjective questionnaire survey.

3.1 Weather conditions

According to the Koppen climate classification system [35], the climate of Tianjin is a monsoon-influenced humid continental climate, characterized by a hot, humid summer and a cold, gloomy winter. Figure 3 shows the average, maximum, and minimum T_a and RH in Tianjin between 1971 and 2003. The average temperature is the highest in July at 26.1^{o}C and the lowest in January at -2.4^{o}C. The maximum temperature is the highest in June at 36.9^{o}C, and the minimum temperature is the lowest in February at -13.9^{o}C. The relative humidity is high in July and August, approaching 80%, and relatively low in the spring.

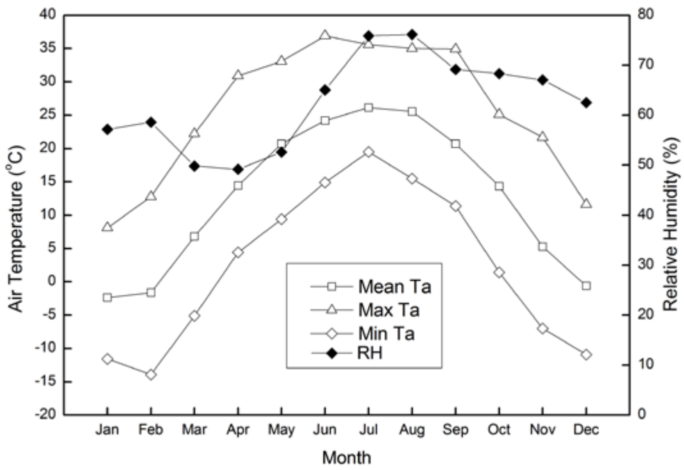

Fig. 3. The monthly mean/maximum/minimum air temperature and mean relative humidity in Tianjin from 1971 to 2003. Source: Meteorological database for thermal environment analysis of Chinese buildings.

The local climate in the park is determined in large part by the widely ranging weather conditions in Tianjin, but the presence of buildings and plants may alter the microclimate to some extent. Table 2 summarizes the mean, maximum, and minimum air temperature, relative humidity, wind speed, and global solar radiation in different seasons as measured at the weather station. The temperature ranged from -5 to 34.5^{o}C and the humidity from 8.4 to 71%. This wide fluctuation in climate conditions corresponded to the typical weather patterns in Tianjin, except that the wind speed was much lower because it was measured at a height of 2 m above the ground in the center of the city. At this location, vegetation and surrounding structures blocked the wind and decreased its speed. As for solar radiation, both sunny days and overcast or cloudy days were included in every season of the survey.

Table 2.Average/maximum/minimum air temperature, relative humidity, wind speed, and global solar radiation as measured in different seasons.

		T_a (^{o}C)	RH (%)	V_a (m/s)	G (W/m^2)
Cold season	Average	3.9	42.5	0.70	278.0
	Max.	15.1	71.0	1.50	570.6
	Min.	-5.0	13.0	0.00	39.4
Shoulder seasons	Average	25.9	29.9	0.45	446.6
	Max.	30.6	57.0	1.50	865.6
	Min.	18.0	8.4	0.00	44.9
Hot season	Average	30.7	56.6	0.27	323.2
	Max.	34.5	70.7	0.70	755.6
	Min.	25.6	42.8	0.00	144.6

3.2 Thermal comfort during the survey

In the following sections, an overall picture is provided of thermal sensation and comfort in different seasons, and then outdoor thermal comfort is discussed with respect to weather parameters and age group.

3.2.1 Thermal sensation and overall comfort

Figure 4 shows the TSV distribution in the cold, shoulder, and hot seasons. In the shoulder seasons, the percentage of people who felt "neutral" (TSV = 0) was the highest (58.6%). In the cold season with a low averaged temperature of 3.9^{o}C, the most frequently perceived thermal sensation was still "neutral" (45.0%), which indicated the high degree of adaptability of Tianjin residents to the cold outdoor environment. In the hot season, the percentage of people who felt "hot" (TSV = 3) was dominant (62.2%).

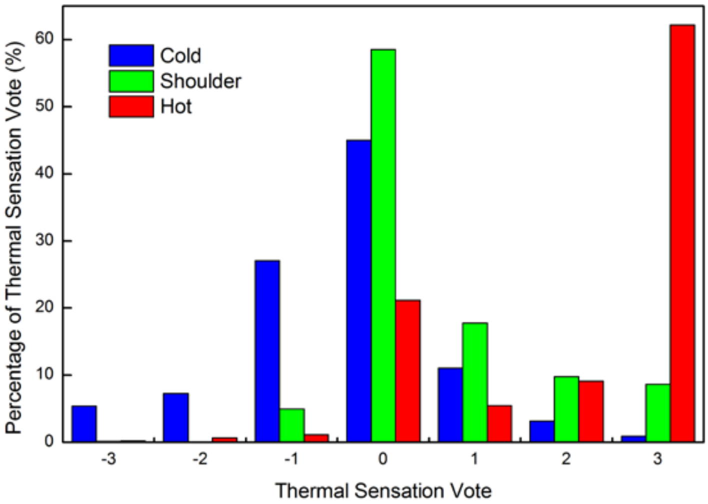

Fig. 4. Thermal sensation votes (TSVs) in different seasons.

Figure 5 shows the distribution of overall comfort. The large percentage of "hot" votes made the hot season the most uncomfortable with a rate of 38.5%. However, the average uncomfortable rate for all seasons was 16.7%, which indicates that the majority of people found the outdoors thermal conditions acceptable (83.3%).

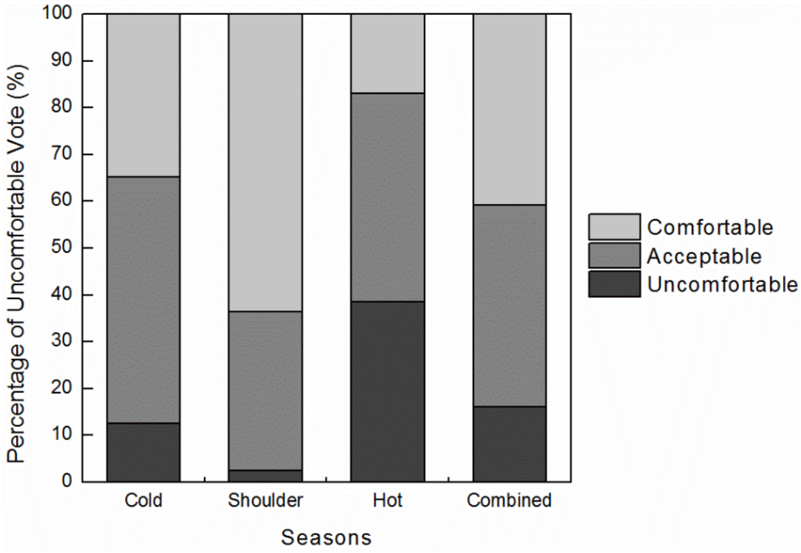

Fig. 5. Overall comfort votes in different seasons.

There were strong correlations between thermal sensation and overall comfort. Figure 6 shows the correlation between each TSV scale and the corresponding averaged comfort vote for different seasons. The correlation can be expressed by the following equations through binominal curve fitting:

Cold season: $y = -0.072x^2 + 0.125x + 0.421$ with $R^2 = 0.898$ (3)

Shoulder seasons: $y = -0.077x^2 + 0.012x + 0.716$ with $R^2 = 0.982$ (4)

Hot season: $y = -0.064x^2 + 0.139x + 0.523$ with $R^2 = 0.975$ (5)

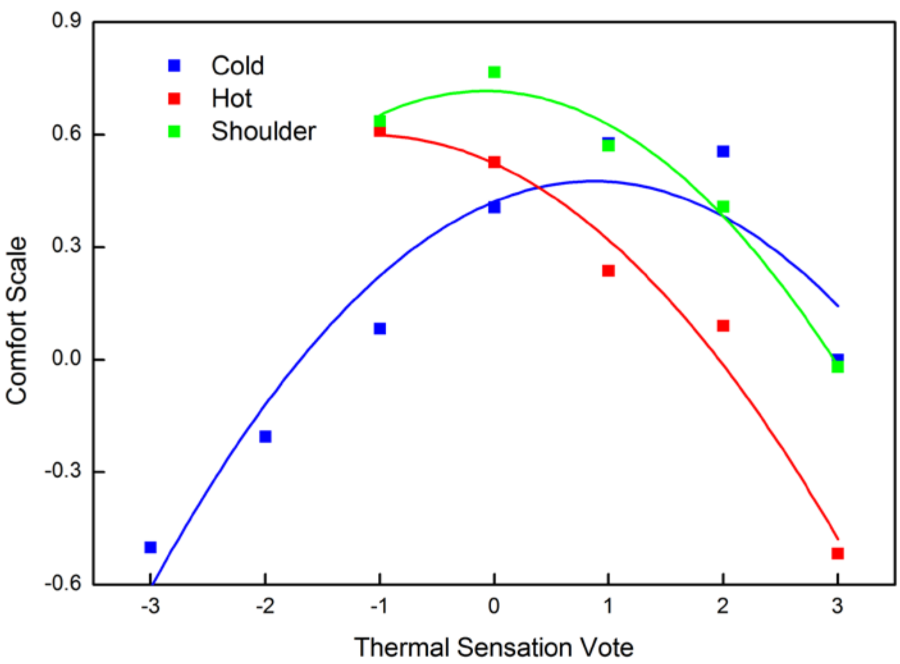

Fig. 6. Correlation between thermal sensation and overall comfort.

The most comfortable condition was at a TSV of 0.86 for the cold season, -0.08 for the shoulder season, and -1.07 for the hot season, which indicates that the correlation changed with the season. "Slightly warm" was considered to be the most comfortable sensation in the cold season, "neutral" in the shoulder seasons, and "slightly cool" in the hot season. This can be attributed to the concept of "Alliesthesia" [2], a psychological mechanism that explains the differences in sensation between seasons: a warm sensation was considered to be more comfortable than a cool sensation in the cold season, and vice versa in the hot season.

Many outdoor studies, such Mahmoud's survey in Cairo, Egypt [12], Yahia's in Damascus, Syria [36], and Kariminia's in Esfahan, Iran [22], have applied the middle three thermal sensation votes (-1, 0, 1) as an acceptable or satisfactory range. However, the current findings indicate that it may be problematic to apply such a range to outdoor settings. For instance, Figure 6 shows that in the cold season, the "warm" sensation (TSV = 2) is much more comfortable than the "slightly cool" sensation (TSV = -1). This asymmetry in overall comfort would probably lead to an asymmetry in acceptability. Thus, because of the varying comfortable or acceptable ranges, direct assessment of thermal acceptability (acceptable or unacceptable) is recommended.

3.2.2 Preference of weather parameters

Outdoor thermal comfort and overall comfort are related to weather parameters. However, the parameters are not of equal importance. To explain the occupants' preferences in outdoor weather parameters, Figure 7 shows their preference votes in different seasons. It can be seen that the temperature and solar radiation preferences changed dramatically with the season. In the cold season, most occupants desired a higher air temperature and more solar radiation, while the situation was reversed in the hot season. Lower humidity and higher air movement were preferred in the hot season. This was not surprising, because high water vapor pressure and low wind speed in the hot season reduce the evaporation rate of moisture from the skin and the rate of convective heat exchange between the skin and ambient air.

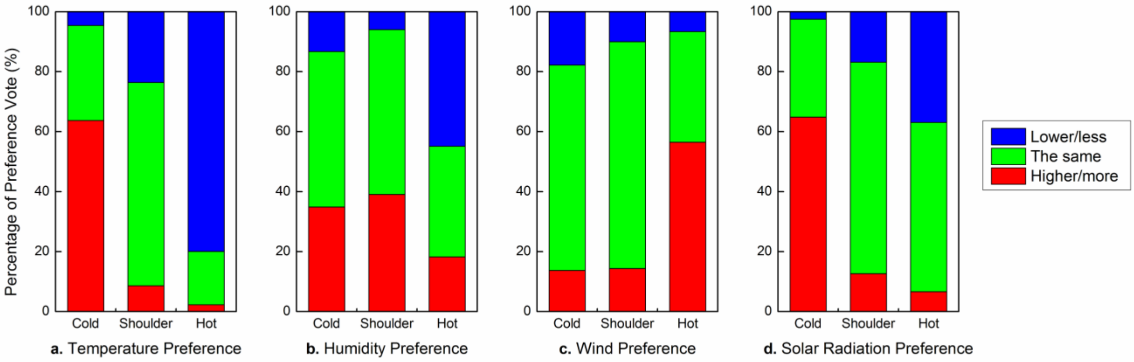

Fig. 7. Preference votes in the cold, shoulder, and hot seasons for different weather parameters: (a) temperature; (b) humidity; (c) wind speed; and (d) solar radiation.

The preferences in outdoor weather parameters were related to the combined meteorological conditions. Because the distribution of preference votes was not normal, this study used the Spearman Rank Order Correlation Coefficient [37] to correlate the preferences with the weather parameters. The coefficient is a non-parametric measure of the strength and direction of association that exists between two variables. Table 3 shows that air temperature has the most significant influence on the preferences. The preference in solar radiation has the strongest correlation (-0.562) with air temperature, followed by the preferences in wind speed (0.484) and relative humidity (-0.349). The sign of the correlation coefficient reveals that the higher the air temperature is, the lower the solar radiation and the relative humidity and the higher the wind speed preferred by the occupants, and vice versa.

Table 3. Correlation analysis between weather parameters and preference votes.

	Preferred Ta	Preferred G	Preferred v	Preferred RH
Ta	N/A	-0.562	0.484	-0.349
G	-0.120	N/A	-0.045	0.071
v	0.215	0.150	N/A	0.083
RH	-0.105	0.066	0.139	N/A

3.2.3 Effect of age group on outdoor thermal comfort

Figure 8 shows the mean thermal sensation, clothing level, and metabolic rate of the three different age groups (children under 20 years old, adults aged between 20 and 60, and seniors over 60) at different air temperature ranges. The thermal sensation of the children was the highest, while that of the seniors was the lowest. The children felt the warmest because they were the most active, as shown in Fig. 8(c). Meanwhile, because of their reduced metabolic rate [38], the seniors felt less warm than the other groups and adapted by wearing more clothing (Fig. 8(b)).

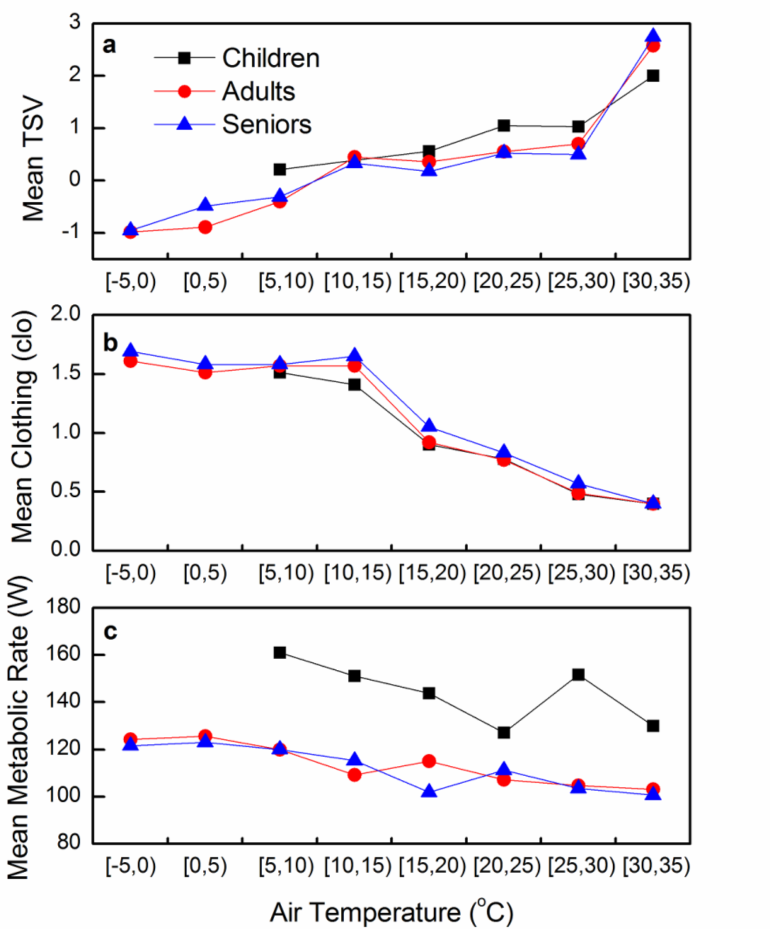

Fig. 8. The effects of air temperature on children, adults, and seniors: (a) mean TSV, (b) mean clothing level, and (c) mean metabolic rate.

For all respondents, TSV gradually increased with air temperature. When the air temperature was below 30°C, the subjects adapted to temperature increase by reducing their clothing and activity levels to keep their thermal sensation between -1 and 1. When the air temperature was above 30°C, the adaptation behavior of the subjects was no longer sufficient to cope with the high temperature. It should be noted that the subjects did not reduce their clothing level when the air temperature increased from -5 to 15°C. As illustrated in Figure 6, a warmer sensation was perceived as more comfortable in the cold season. Therefore the subjects maintained their clothing level in order to achieve a warmer sensation as the temperature increased.

3.3 Assessment of the comfort indices

In addition to the questionnaire survey, this investigation used thermal indices (PMV, PET, and UTCI) to evaluate human thermal comfort. The indices were derived from human energy balance. This study calculated the indices from weather parameters (*Ta, RH, Va, and G*) and human parameters (clothing insulation and activity level). The thermal indices were compared with the thermal sensation votes obtained from the questionnaire surveys.

3.3.1 PMV

PMV was developed for evaluating thermal comfort indoors. In order to assess the applicability of PMV to outdoor thermal comfort, this investigation calculated an hourly PMV using the mean meteorological and human parameters and compared this PMV with the corresponding averaged TSV. Thermal sensation votes with a metabolic rate exceeding 200 W were excluded from the study in order to maintain a relatively uniform metabolic rate for the subjects.

Figure 9 shows the correlation between PMV and TSV. The linear regression line shows that PMV overestimated the thermal sensation by a factor of 1.3. PMV provided a quite accurate prediction at a nearly neutral state (-0.5 to 0.5). Because it was developed in an indoor setting under the assumption of comfortable mean skin temperature and sweat rate, its applicability to an outdoor environment is limited. The wide fluctuations in outdoor thermal parameters results in frequent deviations from the neutral state, and therefore the PMV should not be used.

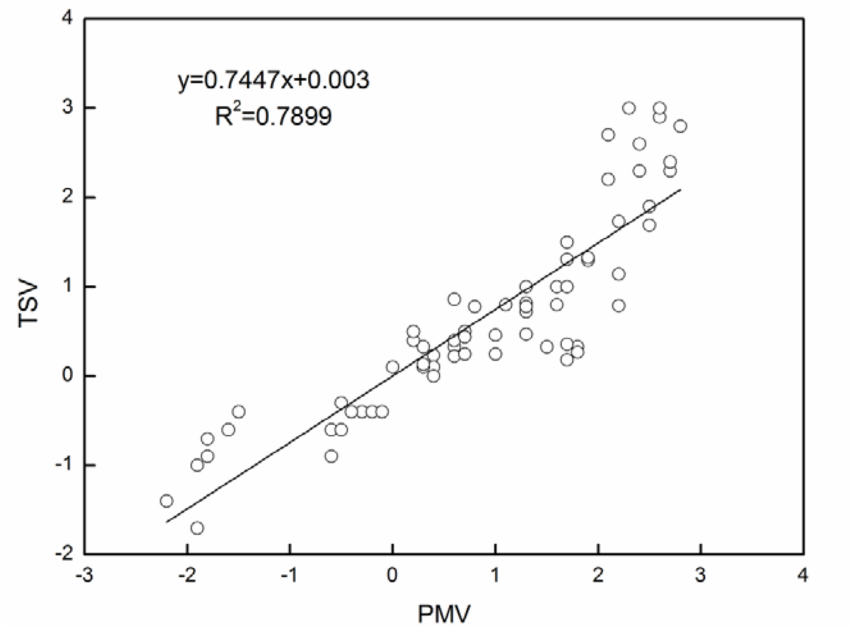

Fig. 9. Correlation between PMV and mean TSV.

3.3.2 PET

PET has been widely used in outdoor studies in various climates to determine the local neutral temperature or thermal sensation. In order to establish a thermal sensation range for PET in northern China, this study used a method similar to that of Lin [39], calculating the mean TSV for every 1 K PET interval. For example, if the mean thermal sensation among the subjects exposed to 20-21^{o}C PET is 0.36, the mean TSV is equal to 0.36 for a PET of 20.5^{o}C. This method was used to calculate the relationship between TSV and PET for the 1585 thermal sensation votes collected in the surveys, as shown in Figure 10.

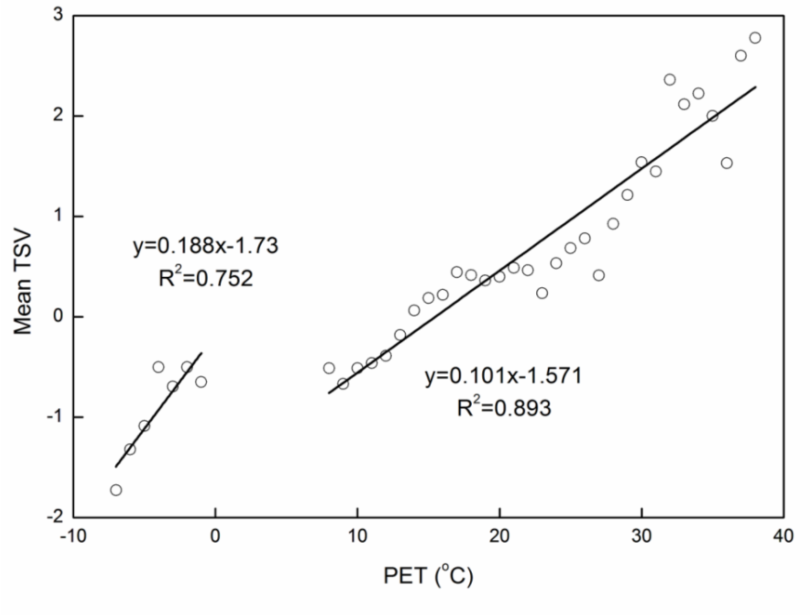

Fig. 10. Relationship between mean TSV and PET.

The data can be divided into two groups. The group of data on the left side of Figure 10 was collected in two field surveys when the air temperatures were below 0°C. The slope of the left regression line is 0.188, which corresponds to 5.3 K PET/TSV. For the group of data on the right side of Figure 10, the slope of the regression line is 0.101, which corresponds to 10 K PET/TSV. The results indicate that Tianjin residents were more sensitive to the colder environment. With the assumptions in Table 4, Table 5 compares the PET range for different thermal sensation votes in Tianjin, Europe, and Taiwan. The data in Tianjin for “Very Cold,” “Cold,” “Cool,” “Hot,” and “Very Hot” were obtained through regression because they were not available from the surveys. The results show that the “neutral” PET ranges in Tianjin (11 to 24°C) are much wider than those in Europe (18 to 23°C) and Taiwan (26 to 30°C). This might be explained by physiological adaption, which is defined as the changes in physiological responses resulting from repeated exposure to a stimulus, leading to a gradual decreased strain from such exposure [25]. Since residents in Tianjin expose themselves to a wider and colder climate (Monthly mean temperature -3 to 26°C) than residents in Taiwan (Monthly mean temperature 16 to 29°C) and in Europe (Freiburg as example: monthly mean temperature 2 to 20°C), the physiological adaption lead them to have a wider and lower thermal sensation range.

Table 4. Assumed TSV for different thermal sensations

Thermal Sensation	TSV
Very Cold	<-3.5
Cold	-2.5 to -3.5
Cool	-2.5 to -1.5
Slightly cool	-1.5 to -0.5
Neutral	-0.5 to 0.5
Slightly warm	0.5 to 1.5
Warm	1.5 to 2.5
Hot	2.5 to 3.5
Very Hot	>3.5

Table 5. Relationship between TSV and PET for Tianjin residents, Europeans, and Taiwanese.

Thermal sensation	PET in Tianjin	PET in Europe [40]	PET in Taiwan [39]
Very cold	< -16 [a]	< 4	< 14
Cold	-16– -11 [a]	4–8	14–18
Cool	-11– -6 [a]	8–13	18–22
Slightly cool	-6–11	13–18	22–26
Neutral	11–24	18–23	26–30
Slightly warm	24–31	23–29	30–34
Warm	31–36	29–35	34–38
Hot	36–46 [a]	35–41	38–42
Very hot	> 46 [a]	> 41	> 42

[a] Sensation obtained by linear regression

3.3.3 UTCI

As with the assessment of PET, this investigation evaluated UTCI by correlating each 1 K UTCI to a mean TSV. Figure 11 shows that the slopes of the correlations for the groups on the left and right sides were 0.183 and 0.13, respectively, which correspond to 5.5 K and 7.7 K UTCI/TSV. Table 6 shows the thermal sensation range for each UTCI stress category. The category of “slight heat stress” is not shown because there is no such category for UTCI. This, according to UTCI Fiala model results, is due to the absence of a physiological response of slight heat stress in the simulation [41]. Using the correlation shown in Table 6, Table 7 illustrates the modified UTCI stress categories for northern China, several of which were obtained by regression. UTCI is supposed to be valid for all climates. However, Table 7 shows substantial differences between the Mediterranean climate [42] and the climate of northern China. The differences can be attributed to the different degrees of adaption to their local climate by the two groups of people. It is worth noting that in the “no thermal stress,” “moderate heat stress,” and “strong heat stress” categories, the ranges for Tianjin are quite close to those for the original UTCI.

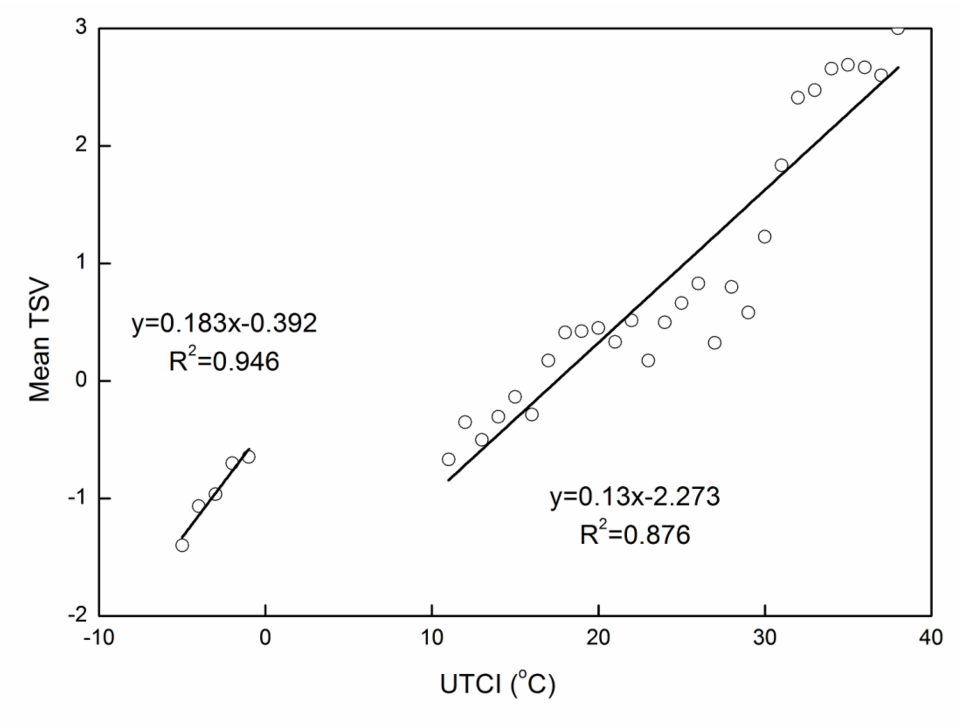

Fig. 11. Relationship between mean TSV and UTCI.

Table 6. Assumed thermal sensations for different stress categories.

Stress category	TSV
Extreme cold stress	< -4.5
Very strong cold stress	-4.5 to -3.5
Strong cold stress	-2.5 to -3.5
Moderate cold stress	-2.5 to -1.5
Slight cold stress	-1.5 to -0.5
No thermal stress	-0.5 to 0.5
Moderate heat stress	0.5 to 2.5
Strong heat stress	2.5 to 3.5
Very strong heat stress	3.5 to 4.5
Extreme heat stress	> 4.5

Table 7. UTCI for different climates.

Stress category	UTCI [21]	Modified UTCI for Mediterranean climate [42]	Modified UTCI for Tianjin, China
Extreme cold stress	< -40	< 4.1	< -21 [a]
Very strong cold stress	-40 to -27	4.1 to 5.9	-21 to -16 [a]
Strong cold stress	-27 to -13	5.9 to 9.1	-16 to -11 [a]
Moderate cold stress	-13 to 0	9.1 to 14.0	-11 to -6 [a]
Slight cold stress	0 to 9	14.0 to 17.4	-6 to 12
No thermal stress	9 to 26	17.4 to 24.5	12 to 25
Moderate heat stress	26 to 32	24.5 to 29.1	25 to 33
Strong heat stress	32 to 38	29.1 to 34.1	33 to 39
Very strong heat stress	38 to 46	34.1 to 37.7	39 to 47 [a]
Extreme heat stress	> 46	> 37.7	> 47 [a]

[a] Sensation obtained through linear regression

4. Conclusion

This paper presented the findings of our outdoor thermal comfort studies in Tianjin, northern China. The investigation conducted field studies in a public park from March 2012 to January 2013. The data were collected 11 times throughout the period by microclimatic monitoring and questionnaire surveys. Analysis of the data led to the following conclusions:

- In the cold and shoulder seasons, "neutral" was the most frequently perceived thermal sensation (58.6% and 45.0% for the cold and shoulder seasons, respectively). In the hot season, the percentage of "hot" votes was the highest (62.2%). The uncomfortable rate for all seasons was 16.7%. The relationship between overall comfort and thermal sensation varied with the season. "Slightly warm" was perceived as the most comfortable sensation in the cold season, "neutral" in the shoulder seasons, and "slightly cool" in the hot season.

- Preferences in solar radiation, wind speed, and relative humidity were linked to air temperature. The higher the air temperature was, the higher the wind speed and the lower the solar radiation and relative humidity preferred by the occupants, and vice versa.

- The children in the surveys felt the warmest because they had the highest activity level. Although the seniors wore more clothing to compensate for their reduced metabolic rates, their thermal sensation was the lowest. When the air temperature rose, occupants adapted by reducing their clothing and activity levels. However, when the temperature was above 30^{o}C, the occupants were not able to adapt to the environment.

- This investigation assessed several comfort indices. The PMV overestimated the outdoor thermal sensation by a factor of 1.3. The UTCI provided a satisfactory prediction of outdoor thermal comfort within the scope of our study. The PET thermal sensation range for northern China was different from the ranges for Europe and Taiwan. The results showed that residents of Tianjin were more adapted to their cold environment.

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