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Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year

Sajad Zare[a], Naser Hasheminejad[a], Hossein Elahi Shirvan[b], Rasoul Hemmatjo[c], Keyvan Sarebanzadeh[b,*], Saeid Ahmadi[d]

[a] Department of Occupational Health, School of Public Health, Kerman University of Medical Sciences, Kerman, Iran
[b] Student Research Committee, Kerman University of Medical Sciences, Kerman, Iran
[c] Department of Occupational Health, School of Public Health, Urmia University of Medical Sciences, Urmia, Iran
[d] Department of Occupational Health, School of Public Health, Qazvin University of Medical Sciences, Qazvin, Iran

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ABSTRACT

Heat stress negatively influences human health and performance, and leading to lower efficiency in daily activities. The present study sought to examine the relationship between UTCI, other heat indices (SET, PET, PMV, PPD, and WBGT), and environmental parameters. Daily data, encompassing a 12 month period in 2016 (from 6 a.m. to 9 p.m. for each day), were retrieved from the Meteorological Organization of Kerman. The data were fed into SPSS 20, followed by conducting Pearson product moment correlation and linear regression to find the association between UTCI and other heat indices/environmental parameters. Excel 2016 was also utilized to draw the relevant diagrams. Significant correlations were detected between UTCI and other heat indices (SET, PET, PMV, and WBGT). UTCI also was measurably correlated with environmental parameters like dry temperature ($P < 0.0001$). The highest correlation coefficient was observed between UTCI and PET ($r = 0.96$). UTCI also had strong correlations with WBGT ($r = 0.88$), SET ($r = 0.87$), and dry temperature ($r = 0.90$). Thus, indices that are calculated based on body thermal equation (i.e. SET and PET) are more strongly connected with UTCI, registering a better slope. On the other hand, WBGT is more similar to UTCI (than other indices) in terms of thermal perception.

1. Introduction

Human activities are influenced by weather conditions (Burton et al., 2009). Indeed, humans are highly sensitive to environmental heat; they may suffer dire consequences as a result of being exposed to environments with high temperatures. For example, heat stroke can cause sudden death or it may damage to the main body organs and physiological functions. It can also increase the likelihood of cardiovascular diseases, and raise the possibility of work-related accidents (Bridger, 2008; Zhao et al., 2015). Climate extremes and climate variability influence all dimensions, including food, water, and natural capital security. Thus, climate change affects these dimensions (Pulwarty and Sivakumar, 2014). Human thermal discomfort is measured by various indices (Burton et al., 2009). Since 1950, numerous reports have discussed human thermal comfort in indoor and outdoor environments, leading to various numerical and diagram-based comparisons (Abdel-Ghany et al., 2013). Over 60 heat stress indices have been proposed to assess high temperature environments and predict the possibility of heat strain for the body. Each of these indices have their own advantages and drawbacks (Burton et al., 2009). The input data for calculating these indices include many atmospheric parameters like airflow velocity, temperature, humidity, solar radiation, and etc. These indices are divided into analytical/rational (based on the principles of human thermal exchange), experimental (based on human response to various environmental factors), and comfort-based (measured through experiments conducted on humans) groups (Huizenga et al., 2006; Pantavou et al., 2014; Parsons, 2006).

The UTCI originates from an approach that was proposed over 10 years ago by the International Society of Biometeorology (ISB) Commission. It was subsequently reinforced by COST Action 730 (Pappenberger et al., 2015). Fiala et al.'s advanced multi-node model of thermo-regulation provides the basis for the UTCI, which is defined as the capability of an organism to retain its body temperature within a particular limit even if the surrounding temperature is totally different

* Corresponding author.
E-mail address: k.sarebanzadeh@gmail.com (K. Sarebanzadeh).

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(Fiala et al., 2012).

Universal thermal climate index (UTCI), introduced in 1994, considers dry temperature, relative humidity, solar radiation, and wind speed into account and is regarded as the reference environmental temperature causing strain (Baaghideh et al., 2016). Standard Effective Temperature (SET) is a rational and the most comprehensive comfort temperature index. It is calculated through two physiological parameters (skin temperature and skin wettedness) (Blazejczyk et al., 2012).

Physiological Equivalent Temperature (PET) is one of the most commonly used indices for measuring heat stress in outdoor spaces. It is the output of Munich Energy Balance Model for Individuals (MEMI) (Esmaili and Montazeri, 2013).

Predicted Mean Vote (PMV), proposed by Fanger, predicts the mean value for a large group of individuals by using four environmental parameters (including dry temperature, radiation temperature, wind speed, and relative humidity) and two human parameters (clothing insulation and metabolic rate) (Fanger, 1972; Lai et al., 2014). Predicted Percentage Dissatisfied (PPD) is calculated based on PMV and its value ranges from 0 to 100.

PMV and PPD are used as the indices for assessing global thermal comfort in buildings which have mechanical cooling (Alfano et al., 2016). The European Standard EN 15251 suggests design ranges of the operative temperatures that are in line with the acceptable level of thermal comfort. As a result, accurate calculation of PMV, PPD, and the relevant operative temperature is very crucial in indoor environmental quality (IEQ) and energy saving (Standard, 2007).

As the most commonly used index of heat stress, the wet-bulb globe temperature (WBGT) was proposed more than 50 years ago. It was first used during the 1950s as a component of a successful campaign to reduce heat-related illnesses in the training camps of the US Army and Marine Corps (Budd, 2008).

Wet Bulb Globe Temperature (WBGT) was suggested by Yaglue and Minard in 1957 ((ISO), 1989). A lot of studies have calculated this index for outdoor spaces based on standard meteorological data. Four parameters – namely dry temperature, relative humidity, wind speed, and radiation heat – are taken into account in calculating this index, which presents a more accurate value in comparison with other simple heat indices like heat index and the humidex (Hyatt et al., 2010).

Since there are various indices to study the effects of heat strain on human health, the present study aimed at:

1 Determining atmospheric parameters of workplace
2 Assessing UTCI, SET, PET, PMV, PPD, and WBGT
3 Examining the correlation between UTCI and environmental parameters (dry temperature, wind speed, and relative humidity)
4 Examining the correlation between UTCI and heat indices (SET, PET, PMV, PPD, and WBGT)

2. Research method

2.1. Study area

This study was conducted in Kerman, a city located at longitude 56° 58 min and latitude 30° 15 min with an elevation of 1753.8 m above sea level. This city is the capital of Kerman Province in the southeastern part of Iran and has an arid climate (Organization, 2017). The study was conducted during the 12 months of 2016.

The geographical location of Kerman within Iran is illustrated in the following map.

2.2. Collecting data related to environmental parameters

Daily data of environmental parameters including dry temperature (°C), wind speed (m/s), and relative humidity (%) were collected from the Meteorological Organization of Kerman. The organization measures these parameters every 10 min during the day. Subsequently, the data were registered between 6 a.m. and 9 p.m. and average values for every 24 h of the first, fifteenth, and thirtieth days of each month were collected and divided into 7 groups (6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., 9 p.m., and the average for the entire 24 h). The values for all indices were calculated in the light of these groups. The amounts of cloudiness and clothing insulation for various seasons and weather conditions of Kerman were taken into account according to Table 1. The metabolic rate was also considered to be 80 w/m^2.

2.3. Calculating heat stress indices (UTCI, SET, PET, PMV, PPD, and WBGT)

2.3.1. Universal thermal climate index

UTCI is the equivalent temperature for the environment derived from a reference environment. It is defined as the air temperature of the reference environment which produces the same strain index value in comparison with the reference individual's response to the real environment. It is regarded as one of the most comprehensive indices for calculating heat stress in outdoor spaces (Blazejczyk, 1994). This index was developed to have a standard criterion for assessing heat stress in the light of human meteorology (Błażejczyk, 2010). The input data for calculating UTCI include meteorological and non-meteorological (metabolic rate and clothing thermal resistance) data (Farajzadeh et al., 2016). The parameters that are taken into account for calculating UTCI involve dry temperature, mean radiation temperature, the pressure of water vapor or relative humidity, and wind speed (at the elevation of 10 m). UTCI is divided into 10 groups ranging from extreme cold stress to extreme heat stress (Table 2) (Young, 2017). The wind speed should range from 0.5 to 17 m/s in order to calculate UTCI (Froehlich and Matzarakis, 2015). In the current study, the wind speed per day and per hour varied from 0.5 to 17 m/s. Bioklima is used to calculate UTCI (Błażejczyk, 2017).

2.3.2. Standard effective temperature

SET, which is a rational index (Gagge, 1971; Gagge et al., 1986), is calculated by taking skin temperature and skin wettedness into account (Blazejczyk et al., 2012). Rayman Version 1.2 was utilized to calculate SET (Blazejczyk, 1994). Given that air temperature and wind speed data are assessed at 10 m level, the input data should be recalculated. Air temperature was approximated through applying a factor of 0.6 K/100 m (Fröhlich and Matzarakis, 2013). Utilizing Hellman's exponential law, wind speed was recalculated for the height of 1.1 m above the surface (Formula 1):

$$V_h = V_{10} \times \left(\frac{h}{h_{10}}\right)^a \tag{1}$$

where V_h is the wind speed (m/s) at height h = 1.1 m, V_{10} is the wind speed (m/s) at height h_{10} = 10 m, and α is the friction coefficient (Hellman exponent). In our study, α is 0.40 (Urban and Kyselý, 2014). Table 3 illustrates the thermal threshold for this index (Blazejczyk et al., 2012).

Table 1
Fixed input values fed into Rayman Version 1.2 and Bioklima.

Months	Metabolic rate (w/m^2)	Cloudiness (octane)	Clothing insulation (Clo)
Jan-Feb-Mar	80	4	1.5
Apr-May-Jun	80	1	0.7
July-Aug-Sep	80	0	0.5
Oct-Nov-Dec	80	2	1.2

Table 2
Thermal sensation and different groups of UTCI.

UTCI (°C) range	above +46	+38 to +46	+32 to +38	+26 to +32	+9 to +26	+9 to 0	0 to −13	−13 to −27	−27 to −40	below −40
Stress Category	extreme heat stress	very strong heat stress	strong heat stress	moderate heat stress	no thermal stress	slight cold stress	moderate cold stress	strong cold stress	very strong cold stress	extreme cold stress

Table 3
Assessing heat stress based on SET.

Category	Thermal sensation	Physiological Stress
<17	Cool	Moderate Hazard
17–30	Comfortable	No Danger
30–34	Warm	Caution
34–37	Hot	Extreme caution
>37	Very Hot	Danger

2.3.3. *Physiological equivalent temperature*

PET is an index derived from the human energy balance equation (Höppe, 1999, 1984). Dry temperature, relative humidity, wind speed, and mean radiant temperature are used to calculate PET. Rayman Version 1.2 was used to calculate this index (Matzarakis, 2007; ZOU, 2008). Since air temperature and wind speed data are measured at 10 m level, we had to recalculate the input data. Through applying a factor of 0.6 K/100 m, air temperature was approximated (Fröhlich and Matzarakis, 2013). Utilizing Hellman's exponential law, wind speed was recalculated for the height of 1.1 m above the surface (Urban and Kyselý, 2014).

Table 4 displays PET values for various levels of thermal perception and physiological stress (Matzarakis et al., 1999).

2.3.4. *Predicted mean vote*

PMV, which was suggested by Fanger in 1970, is one of the main temperature-physiological indices which is frequently used in both urban and regional planning studies as well as meteorological research projects (Matzarakis, 2001; Najafi and Najafi, 2012). This index is used to predict the collective perception of a group of individuals positioned in the same environmental condition (Błażejczyk, 2010; Najafi and Najafi, 2012). Six factors (dry temperature, mean radiation temperature, relative humidity, wind speed, metabolic rate, and clothing insulation) are used to calculate PMV. The value of this index is reported on a seven point scale that ranges from −3 to +3, with 0 being the ideal value indicating neutral thermal perception (Błażejczyk, 2010). Table 5 illustrates the categorization of PMV (Matzarakis et al., 1999). Rayman Version 1.2 was exploited to calculate this index (Blazejczyk, 1994). Since air temperature and wind speed data are measured at 10 m level, the input data need to be recalculated. Air temperature was approximated by applying a factor of 0.6 K/100 m (Fröhlich and Matzarakis, 2013). Wind speed was recalculated for the height of 1.1 m above the surface, using Hellman's exponential law (Urban and Kyselý, 2014).

2.3.5. *Predicted percentage dissatisfied*

PPD estimates the percentage of people who are dissatisfied with heat or cold. PPD is calculated based on PMV and its value ranges from 0 to 100. This index was calculated based on ISO 7 730 standard (Standardization, 2017).

Table 4
Categorization of PET for various levels of thermal perception and physiological stress.

PET	Thermal perception	Grade of physiological Stress
<4	Very cold	Extreme cold stress
4–8	Cold	Strong cold stress
8–13	Cool	Moderate cold stress
13–18	Slightly cool	Slight cold stress
18–23	Comfortable	No thermal stress
23–29	Slightly warm	Slight heat stress
29–35	Warm	Moderate heat stress
35–41	Hot	Strong heat stress
>41	Very hot	Extreme heat stress

Table 5
Categorization of PMV for different levels of thermal perception and physiological stress.

PMV	Thermal perception	Grade of physiological Stress
−3	Very cold	Extreme cold stress
−2.5	Cold	Strong cold stress
−1.5	Cool	Moderate cold stress
−0.5	Slightly cool	Slight cold stress
0	Comfortable	No thermal stress
0.5	Slightly warm	Slight heat stress
1.5	Warm	Moderate heat stress
2.5	Hot	Strong heat stress
3	Very hot	Extreme heat stress

2.3.6. *Wet-bulb globe temperature*

WBGT was developed by Yaglou and Minard in 1957 and is regarded as one of the main experimental indices for measuring heat stress (Yaglou and Minaed, 1957). It can be used to assess heat stress both indoors and outdoors. Depending on where a person is, different variables, including natural wet temperature, radiation temperature, and metabolic rate, are used in calculating this index (Haji Azimi et al., 2011). For indoor spaces, natural wet temperature and bulb globe temperature are utilized in calculating this index, while, for outdoor spaces, dry temperature is also taken into account (Hemmatjo et al., 2013). Table 6 provides necessary recommendations for being involved in outdoor activities according to WBGT values (Blazejczyk et al., 2012). Bioklima was used to calculate WBGT (Błażejczyk, 2017).

2.3.7. *Comparing thermal perceptions of UTCI, SET, PET, PMV, PPD, and WBGT according to standard values for each index*

Table 7 presents comparison of thermal perceptions based on the abovementioned indices (Blazejczyk et al., 2012; Höppe, 1999; Young, 2017).

2.3.7.1. *Ethical considerations.*

Ethical approval was obtained from the Ethics Committee of Kerman University of Medical Sciences (ID: IR. KMU.REC.1 395.637).

2.3.7.2. *Statistical analysis.*

Collected data were analyzed by Statistical Package for the Social Sciences (SPSS) 22 (SPSS Inc., Chicago, IL, USA) using statistical tests such as Pearson correlation coefficient and linear regression. In addition, Excel 2016 was used to draw diagrams. The statistical significance level was set at $P < 0.05$.

Table 6
Necessary recommendations for outdoor activities according to WBGT values.

WBGT (°C)	Recommended sporting activity
<18	Unlimited
18–23	Keep alert for possible increases in the index and for symptoms of heat stress
23–28	Active exercise for unacclimatized persons should be curtailed
28–30	Active exercise for all but the well-acclimated should be curtailed
≥30	All training should be stopped

Table 7
Comparing thermal perceptions in various bioclimatic indices.

Thermal perception	Indices				
	UTCI	WBGT	SET	PMV	PET
Very cold[1] (Extreme cold stress[1,2])	< -40			-3	<4
(very strong cold stress[2])	-40 to -27				
Cold[1] (Strong cold stress[1,2])	-27 to -13			-2.5	4-8
Cool[1,3] (Moderate cold stress[1,2]/ Moderate Hazard[3])	-13 to 0		<17	-1.5	8-13
Slightly cool[1] (Slight cold stress[1,2])	0 to +9			-0.5	13-18
Comfortable[1,3] (No thermal stress[1,2]/ No Danger[3,4])	+9 to +26	<18	17-30	0	18-23
Slightly warm[1] (Slight heat stress[1])				0.5	23-29
Warm[1, 3,4] (Moderate heat stress[1,2]/ Caution[3,4])	+26 to +32	18-23	30-34	1.5	29-35
Hot[1, 3,4] (Strong heat stress[1,2]/ Extreme caution[3,4])	+32 to +38	23-28	34-37	2.5	35-41
(very strong heat stress[2])	+38 to +46				
Very hot[1, 3,4] (Extreme heat stress[1,2]/ Danger[3,4])	> +46	28-30	>37	3	>41
Sweltering[4] (extreme danger[4])		≥30			

[1] PET and PMV [2]UTCI [3]SET [4] WBGT

3. Results

3.1. Mean and standard deviation of environmental parameters

Table 8 shows mean and standard deviation of environmental parameters including dry temperature, relative humidity, and wind speed for the twelve months of 2016. It should be noted that a huge table was required for presenting the mean values for every measurement hour (6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., and 9 p.m.). Because of lack of enough space, we did not present this table in the current paper and were only confined to demonstrating the monthly mean scores and standard deviations. The highest and lowest wind speed (m/s) during the 12 months, respectively belonged to July (3.97 ± 1.20) and November (2.04 ± 0.88), respectively. Also, the maximum and minimum relative humidity were registered in November (42.91 ± 8.01) and July (7.42 ± 1.31), respectively. Finally, the highest dry temperature (°C) mean score was recorded in June (31.36 ± 1.13), whereas the lowest value was registered in December (8.18 ± 2.36).

3.2. The values of UTCI, SET, PET, PMV, PPD, and WBGT

Table 9 displays mean and standard deviation of calculated indices for the twelve months of 2016. A huge table was required for presenting the mean values for every measurement hour (6 a.m., 9 a.m., 12 p.m., 3 p.m., 6 p.m., and 9 p.m.). Due to lack of space, we did not present this table in the current paper and were only confined to demonstrating the monthly mean scores and standard deviations. The highest mean scores for UTCI (26.14 ± 5.74), SET (20.87 ± 5.40), PMV (1.41 ± 0.72), and WBGT (18.69 ± 1.40) were recorded in July. On the other hand, the maximum mean scores for PET (29.00 ± 2.19) and PPD (83.33 ± 6.52) were observed in July and December, respectively. It should be noted that UTCI significantly correlated with SET, PET, PMV, and WBGT ($P < 0.0001$).

3.3. The correlation between UTCI and environmental parameters/other indices

3.3.1. The correlation between UTCI and environmental parameters (dry temperature, wind speed, and relative humidity)

As observed in Table 10, UTCI significantly correlated with environmental parameters including dry temperature, relative humidity, and wind speed ($P < 0.0001$). More precisely, UTCI had a strong correlation with dry temperature ($r = 0.89$), while it had a negative correlation with relative humidity ($r = -0.67$). The lowest correlation coefficient was recorded between UTCI and wind speed ($r = 0.29$). The following equation indicates the simple linear regression equation between UTCI and dry temperature: $\text{UTCI} = 1.03 \times \text{Ta} + 2.58$.

Fig. 2 represents the scatterplots and regression lines for the relationship between UTCI and environmental parameters.

3.3.2. The correlation between UTCI and SET, PET, PMV, PPD, and WBGT

As indicated in Table 11, UTCI significantly correlated with SET, PET, PMV, and WBGT ($P < 0.0001$). However, no measurable correlation was detected between UTCI and PPD ($r = 0.06$, slope = 0.02). The highest correlation coefficient was observed between UTCI and PET ($r = 0.96$), with the correlation slope being close to 1 (slope = 0.89).

Fig. 3 displays the scatterplots and regression lines for the relationship between UTCI, on the one hand, and SET, PET, PMV, PPD, and WBGT, on the other hand.

3.4. Comparing the monthly mean scores of UTCI with those of SET, PET, PMV, WBGT, and environmental parameters (dry temperature and relative humidity)

Fig. 4 presents a comparison of monthly mean scores for UTCI with those of SET, PET, PMV, WBGT, and environmental parameters (dry temperature and relative humidity) for the twelve months of 2016.

Table 8
Mean and standard deviation of environmental parameters for the twelve months of 2016.

Hour	Parameters		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
24-h mean	Wind Speed (m/s)	Mean	2.24	2.74	2.07	3.07	3.41	3.48	3.97	3.66	2.48	2.24	2.04	1.96
		SD[a]	1.81	1.42	0.67	1.25	1.39	0.87	1.20	1.08	1.04	0.70	0.88	1.03
	Humidity (%)	Mean	20.18	39.58	38.28	22.41	11.38	7.83	7.42	11.04	17.73	19.03	42.91	29.11
		SD	7.35	10.55	14.11	9.22	3.82	1.93	1.31	2.56	7.47	4.37	8.01	10.17
	dry temperature (^{0}C)	Mean	9.99	9.54	13.72	20.92	28.09	31.36	29.81	27.83	25.40	23.17	12.61	8.18
		SD	3.91	4.76	5.22	3.50	2.50	1.13	1.38	1.09	2.83	1.47	2.93	2.36

[a] SD, Standard Deviation.

Table 9
Mean and standard deviation of calculated indices for the twelve months of 2016.

Hour	Indices		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
24-h monthly mean	UTCI	mean	1.53	1.68	7.77	13.87	19.29	26.14	21.69	20.03	17.95	13.83	8.73	1.68
		SD	4.60	3.48	4.62	3.72	1.50	5.74	1.54	1.54	1.33	2.45	5.47	3.48
	SET	mean	11.44	12.62	15.15	12.52	20.34	20.87	19.89	17.37	15.56	19.30	11.08	7.75
		SD	2.30	2.04	3.70	3.34	1.53	5.40	2.40	1.21	3.74	1.13	2.25	2.22
	PET	mean	5.70	6.67	11.01	17.90	27.02	27.53	29.00	26.26	23.61	20.99	8.86	5.08
		SD	3.36	3.41	5.80	3.36	2.05	6.93	2.19	1.12	3.65	1.76	2.67	2.54
	PMV	mean	−1.64	−1.34	−1.12	−1.75	−1.49	1.41	−0.62	−1.72	−1.83	−1.33	−1.88	−2.18
		SD	0.18	0.16	0.26	0.56	0.43	0.72	1.09	0.82	0.90	0.20	0.38	0.18
	PPD	mean	58.20	42.67	32.27	63.60	50.37	47.21	37.50	54.33	64.20	42.43	69.50	83.33
		SD	9.68	8.13	12.75	27.59	21.87	44.14	14.19	31.17	18.88	10.06	18.77	6.52
	WBGT	mean	−0.53	3.71	1.33	9.72	9.54	18.69	13.50	11.33	9.29	7.71	6.77	−3.18
		SD	4.00	4.55	4.04	1.46	0.67	1.40	2.58	2.34	1.72	0.96	4.81	2.62

Table 10
The results of correlation between UTCI and environmental parameters.

Environmental parameters	R	R^2	Slope	P-value
Wind Speed	0.29	0.09	1.93	<0.0001
Relative humidity	−0.67	0.45	−0.40	<0.0001
Dry temperature	0.89	0.80	1.03	<0.0001

Fig. 1. Kerman's location in Iran (30°15′N 56°58′E).

3.5. *Comparing heat stress based on UTCI, SET, PET, PMV, and WBGT*

Table 12 provides a comparison of the monthly mean scores for each index (also see Table 7).

4. Discussion

The present study aimed at comparing the correlations between UTCI and other heat indices (SET, PET, PMV, PPD, and WBGT) in Kerman during various hours over the twelve months of 2016. The highest mean score of dry temperature was recorded in June.

On the other hand, significant correlations were detected between UTCI and environmental parameters of dry temperature, relative humidity, and wind speed ($P < 0.0001$). The strongest correlation coefficient was observed in the association between UTCI and dry temperature ($r = 0.87$), with a slope of 1.03. Blazejczyk et al. (2012) and Vatani et al. (2016) also demonstrated the strong correlation between UTCI and dry temperature. Vatani et al. (2016) further indicated a significant positive association between UTCI and wind speed (Blazejczyk et al., 2012; Vatani et al., 2016), which is similar to our findings.

The results of this study indicated a negative relationship between UTCI and relative humidity ($r = -0.67$), with a very low slope of −0.40.

Additionally, comparison of mean scores for various indices over different months of 2016 and those of dry temperature and relative humidity showed that all indices are positively related to dry temperature and inversely associated with relative humidity. Thus, a rising trend could be observed in all indices from January to June (with the peak being recorded in June). In contrast, these indices experienced a falling trend over other months of the year (Fig. 4). Moreover, the mean scores of UTCI in all months of the year were smaller than those of dry temperature. Conversely, Ketterer et al. showed that only in the coldest months were UTCI mean values smaller than those of dry temperature (Ketterer and Matzarakis, n.d.). Similar to Ketterer et al. we discovered that variations in wind speed are more influential (than fluctuations in relative humidity and dry temperature) in changing UTCI (Ketterer and Matzarakis, n.d.).

With respect to thermal perception, it was found that WBGT is more similar to UTCI in comparison with other indices. Therefore, similar thermal perceptions were detected in both UTCI and WBGT from April through October, while in other months (cold months of the year), a more severe cold perception was registered for UTCI in comparison to WBGT. Further, SET and UTCI were similar in terms of thermal perception from May to October; however, the most severe cold perception was observed for SET in comparison to UTCI in other months (save for June). In addition, the most severe heat perception was observed for PET (in comparison with UTCI) from May to September. For other months, however, the most severe cold perception was detected for this index. Finally, the most severe cold perception was observed for PMV rather than UTCI during all months of the year except June.

Blazejczyk et al. investigated the correlation between UTCI and other indices, demonstrating that UTCI registered correlation coefficients of 0.97 and 0.96 with SET and PET, respectively (Blazejczyk et al., 2012). Park et al. used UTCI to examine human thermal sensation on human bioclimatic maps in summer, 2009. They showed that UTCI was closely connected with PET ($r = 0.983$), PMV ($r = 0.979$) and SET ($r = 0.957$) (Park et al., 2014) Farajzadeh et al. compared heat indices in the north of Iran from 1986 to 2007. They revealed that UTCI strongly correlated with PET ($r = 0.90$) and SET ($r = 0.94$) (Farajzadeh et al., 2015). Furthermore, Matzarakis et al. demonstrated that the correlation coefficient between UTCI and PET was 0.936 (Matzarakis et al., 2014) The results of these three studies (Blazejcyk et al., 2012; Farajzadeh et al., 2015; Matzarakis et al., 2014) are similar to our findings. In particular, the results of the current study demonstrated that UTCI is strongly associated with PET ($r = 0.96$) and SET ($r = 0.87$) ($P < 0.0001$).

In the present study, the strongest correlation was observed between UTCI and PET ($r = 0.96$). Conversely, in Blazejczyk et al.'s and Farajzadeh et al.'s study, the highest correlation was reported between UTCI and SET (Blazejczyk et al., 2012; Farajzadeh et al., 2015).

In addition, the results of this study yielded a strong correlation between UTCI and WBGT ($r = 0.88$). In contrast, Blazejczyk et al. and

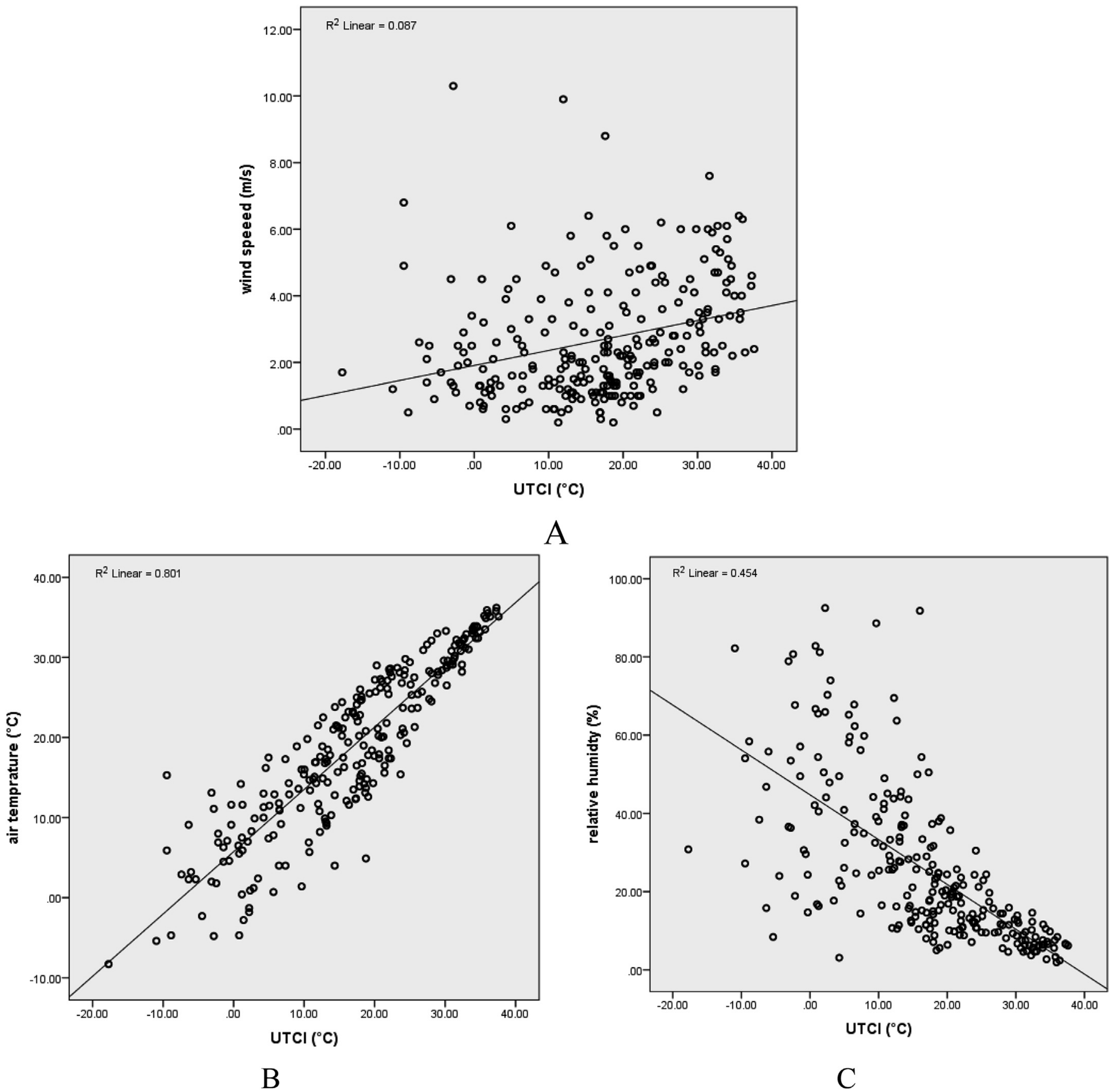

Fig. 2. The scatterplot and regression lines indicating the relationship between UTCI and environmental parameters (A) the scatterplot and regression line showing the relationship between UTCI and wind speed; (B) the scatterplot and regression line showing the relationship between UTCI and dry temperature; (C) the scatterplot and regression line showing the relationship between UTCI and relative humidity.

Table 11
The correlation between UTCI and SET, PET, PMV, PPD, and WBGT.

Indices	R	R^2	Slope	P-value
SET	0.87	0.75	1.18	<0.0001
PET	0.96	0.92	0.89	<0.0001
PMV	0.79	0.63	4.16	<0.0001
PPD	0.06	0.00	0.02	0.32
WBGT	0.88	0.77	1.53	<0.0001

Farajzadeh et al. respectively reported correlation coefficients of 0.42 and 0.77 between these two indices (Blazejczyk et al., 2012; Farajzadeh et al., 2015). Vatani et al. also demonstrated that UTCI and WBGT had a significant, though moderate, relationship ($r = 0.54$) in outdoor spaces.

There were some limitations in this study. For example, we did not have access to weather data before 2016. The data were related to the meteorological stations, which cannot reflect indoor spaces.

5. Conclusions

It is concluded that, in the current study, UTCI had the highest correlation coefficients with PET ($r = 0.96$), WBGT ($r = 0.88$), and SET ($r = 0.87$). Furthermore, it was discovered that, in terms of thermal perception, UTCI is more similar to WBGT compared with other indices.

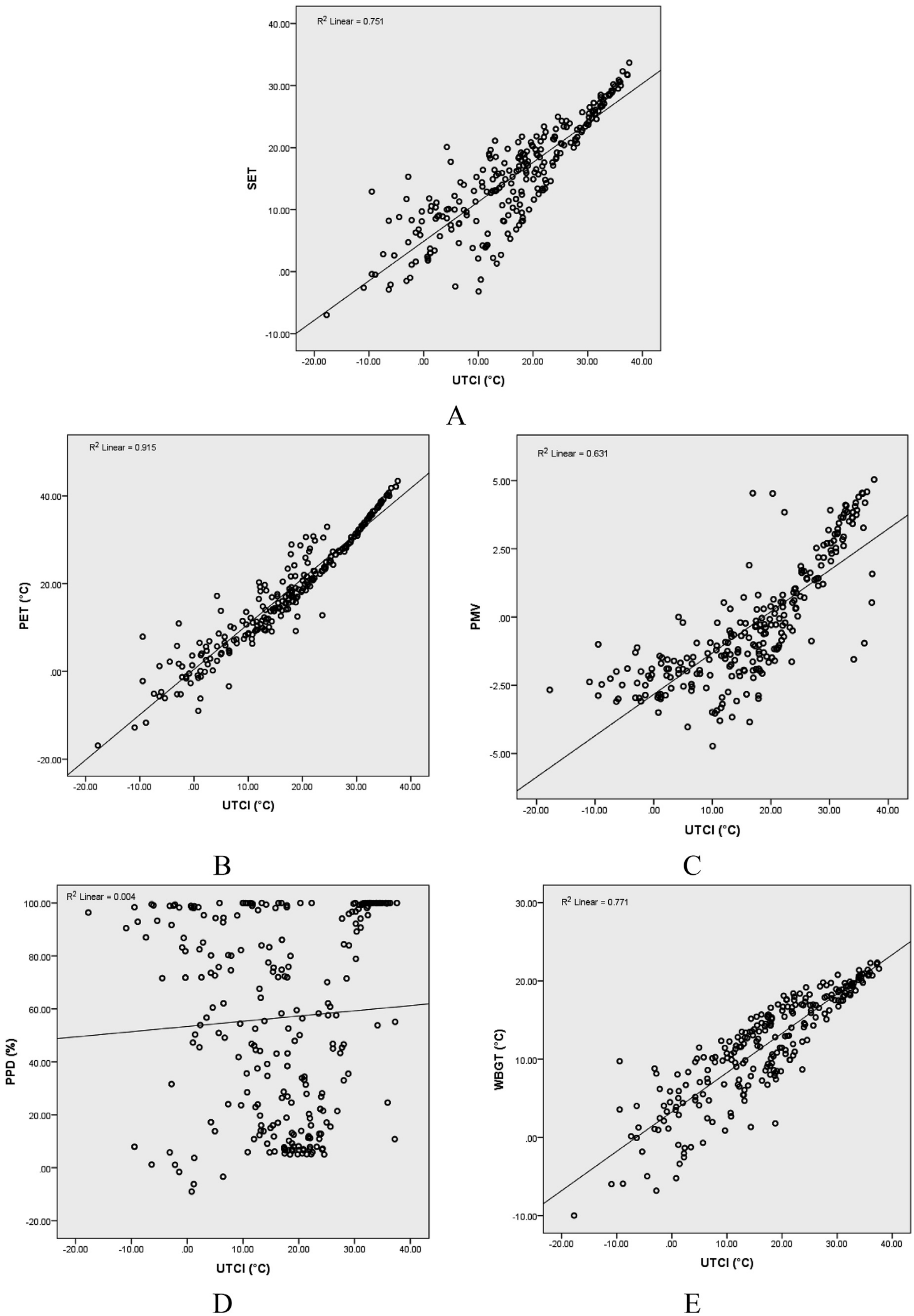

Fig. 3. The scatterplots and regression lines indicating the relationship between UTCI and other indices: (A) the scatterplot and regression line showing the relationship between UTCI and SET; (B) the scatterplot and regression line showing the relationship between UTCI and PET; (C) the scatterplot and regression line showing the relationship between UTCI and PMV; (D) the scatterplot and regression line showing the relationship between UTCI and PPD; (E) the scatterplot and regression line showing the relationship between UTCI and WBGT.

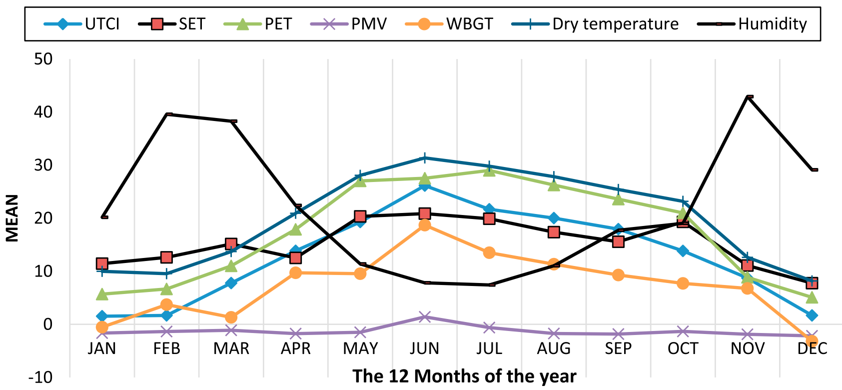

Fig. 4. Comparison of monthly mean scores of UTCI with those of SET, PET, PMV, WBGT, and environmental parameters (dry temperature and relative humidity).

Table 12
Comparison of heat stress based on UTCI, SET, PET, PMV, and WBGT.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
UTCI	1.53	1.68	7.77	13.87	19.29	26.14	21.69	20.03	17.95	13.83	8.73	1.68
SET	11.44	12.62	15.15	12.52	20.34	20.87	19.89	17.37	17.56	19.30	11.08	7.75
PET	5.70	6.67	11.01	17.90	27.02	27.53	29.00	26.26	23.61	20.99	8.86	5.08
PMV	-1.64	-1.34	-1.12	-1.75	-1.49	1.41	-0.62	-1.72	-2.83	-1.33	-1.88	-2.18
WBGT	-0.53	3.71	1.33	9.72	9.54	18.69	13.50	11.33	9.29	7.71	6.77	-3.18

[1] PET and PMV [2]UTCI [3]SET [4] WBGT

In order to generalize the findings to other regions, the authors recommend that a similar study be conducted in other climates (including hot, humid, cold, and dry conditions). It is also recommended that (if possible) the meteorological data for several years should be used and the results should be compared with the ones obtained in this study. Finally, through conducting broader studies, the correction coefficients for converting UTCI to other indices can be determined.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.wace.2018.01.004.

Conflicts of interest

The authors declare no conflicts of interest.

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