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Comparison of selected thermal indices in the northwest of Iran

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Abstract
The present study compared simple thermal indices and the indices derived from energy budget models in the northwest of Iran. For this purpose, the air temperature, solar radiation, relative humidity, cloud, cover and wind speed of 13 meteorological stations in the northwest of Iran during the the period of 1986 to 2007 were selected for comparison. The results which were extracted using Bioklima and RayMan models, showed that the indices based on human energy balance had a significant correlation with each other (with R^2 above 90%), and the lowest R^2 (70%) was related to Subjective temperature index (STI). The indices based on relatively simple formulas had low correlation with Universal Thermal Climate Index (UTCI) and Physiologically Equivalent Temperature (PET). The probable reason for this lack of conformity was the lack of radiation factor in the equations. Furthermore, UTCI was very sensitive to the changes in air temperature, solar radiation, relative humidity and wind speed, especially. In this regard, it represented the response of the human body. The findings of this analysis indicated that UTCI and PET indices were the most suitable indices which could be used in determining thermal comfort conditions.

Keywords
human thermal comfort, meteorological variables, northwest Iran, thermal indices.

1. Introduction
The growing need for valid assessment procedures for outdoor thermal environment in the fields of public weather services, public health systems, urban planning, tourism, recreation, and climate impact research led to the development of thermal indices (Jendritzky et al., 2012). In some studies, the authors addressed issues such as heat waves, climatic variability studies (Nastos and Matzarakis 2008; Matzarakis and Nastos 2011), the effect of weather on health (Nastos and Matzarakis 2006), and/or the effect of climate change on thermal comfort (Matzarakis and Endler 2010; Cheung and Hart, 2014).

Thermal comfort has been the focus of some studies since the beginning of the 20th century (Brager and de Dear, 1998). Since 1905, about 162 different thermal comfort indexes have been developed (De Freitas and Grigorieva, 2015). More than 100 simple thermal indices, mostly two

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parameter indices, have been developed in the last 150 years in order to describe the complex conditions of heat exchange between the human body and its thermal environment. Simple thermal models have been extensively used for the assessment of humans in the thermal environment. For example, simple thermal indices such as, ET[1] or WBGT[2] referred to thermal models, Similarly, there are other thermal models such as rational indices, which include heat stress index (Parsons, 2014). Fanger (1970), Landsberg (1972), Givoni (1976), Driscoll (1992) and Parsons (2003, 2014) offered excellent reviews on this topic. However, these indices can never fulfil the essential requirement for each index value; there must always be a corresponding and unique thermo- physiological state, regardless of the combination of the meteorological values of the input. Thus, their use is limited, the results are often not comparable, and additional features such as safety thresholds have to be defined arbitrarily.

In the 1970s and 1980s, the development and usage of energy balance models of the human body came within the focus of human biometeorology (Höppe, 1997). The thermal indices, which were primarily used for thermal comfort studies, revealed some crucial points. From the point of view of human-biometeorology, they did not include the effects of short and long wave radiation fluxes which are generally not available in climate records (Matzarakis, 2007). For the human energy balance, the required short and long wave radiation fluxes were calculated using synoptic/climatological and astronomical data (VDI, 1998; Matzarakis et al., 2000). A full application of thermal indices of the energy balance of the human body gave detailed information on the effect of the thermal environment of humans (VDI, 1998). Some common applications are PMV[3] and PET[4] (Matzarakis and Mayer, 1997; VDI, 1998; Höppe, 1999; Matzarakis et al., 1999), SET[5] (Gagge et al., 1986) or Outdoor Standard Effective Temperature (Out_SET) (Spagnolo and de Dear, 2003), and UTCI[6] (Havenith et al., 2012; Fiala et al., 2012; Jendritzky et al., 2012.

Although, each of the energy budget models aforementioned, are in principle, appropriate for use in any kind of assessment of the thermal environment, none of them is accepted as a fundamental standard, either by researchers or by end-users. This is probably because of persistent shortcomings of thermo-physiology and heat exchange theory. On the other hand, it is surprising that, after 40 years of experience with energy budget modelling and easy access to both computational power and meteorological data, crude and simplistic empirical indices like WBGT have gained continuous wide usage (Jendritzky et al., 2012).

In UTCI, the dependency of the on wind speed seems very high, especially at lower air temperatures. An increase in wind speed over 30 m/s results in a rapid decrease in the values of the UTCI (Novak, 2013). However, the advantage of these thermal indices is that they require the same meteorological input parameters which include, air temperature, air humidity, wind speed, short and long wave radiation fluxes.

In some studies, attempts were made to evaluate two or three indices of simple thermal indices (Tejeda-Martinez and García-Cueto, 2002; Epstein and Moran, 2006; Eludoyin, 2014; Eludoyin et al., 2014). Also, some researchers made comparison of simple indices with PET index (Farajzadeh and Matzarakis, 2009, 2012; Tseliou et al., 2010; Basarin et al., 2014). In recent years, several studies have been conducted in order to compare and evaluate the indices derived from energy budget models. The results from the findings indicated a close similarity between the result of these indices (Jendritzky et al., 2012; Nastos and Matzarakis, 2012; Bleta et al., 2014; Urban and Kysely, 2014; Fröhlich and Matzarakis, 2015). Concerning the geographical focus of this study, the northwest of Iran is one of the coldest areas in Iran. Therefore, the main objective of this study is to identify the index or indices that are able to show the conditions of thermal comfort clearly throughout the year.

This study selected UTCI to represent thermal comfort and stress in this region for several reasons. First, it is a newly developed index, Therefore, it will be interesting to see which

1. Effective Temperature
2. Wet-Bulb-Globe-Temperature
3. Predicted Mean Vote
4. Physiologically Equivalent Temperature
5. Standard Effective Temperature
6. Universal Thermal Climate Index

selected thermal indices have a good correlation. In addition, compared to other indices, UTCI is more sensitive to the changes in all ambient stimuli (air temperature, solar radiation, humidity, and wind speed) (Blazejczyk et al., 2012), whereas other indices are more sensitive in one parameter (e.g., PET is related more closely to air temperature and OUT_SET is more sensitive to the cooling effect of wind) (Jendritzky et al., 2012).

2. Study area

The northwest of Iran was chosen for the purpose of this study. Figure 1 represents the geographical location of the stations of the northwest Iran. It is characterized by a mountainous region in which the winters are cold and snowy. In this region, spring and autumn are relatively mild, while summers are dry and warm. The climate in this region is classified as 'Csa' Mediterranean climate according to the Köppen-Geiger climate classification. The mean annual rainfall is 310 mm. Maximum rainfall occurs in the southwest stations where the mean annual rainfall amounts to more than 400 mm. The average annual temperature of the stations in this region is 12°C. The provinces located in this region include, West Azarbaijan, East Azarbaijan, Zanjan, Kurdistan and Ardabil. The zone of minimum temperature is located in the capital of Ardebil Province, and the maximum temperature is associated with the northern regions of East Azerbaijan Province, with Tabriz as its capital. Additionally, the greater part of the provinces of eastern Azerbaijan, Kurdistan (with Sanandaj as its capital) and the north of Ardebil have temperatures higher than the average, whereas the center and south of Ardebil Province are colder than the other regions. The stations under the focus of the present study are presented in Table 1.

3. Materials and Methods

The daily data on air temperature, relative humidity, cloud cover, and wind speed for the northwest of Iran, for the period of 1986to 2007, were obtained from the Iran Meteorological Organization (Table 1 and Fig. 1).

The indices were into two groups: simple indices and the indices derived from energy budget models. For the purpose of this study, TEK[1], ET, WCT[2], WBGT, and Humidex were used as the selected simple indices.

The indices derived from energy budget models, namely PET, SET, PST[3], and STI[4] were selected for the purpose of comparison with UTCI.

TEK, Humidex, WBGT, WCT, ET, PST, and STI indices were calculated using BioKlima 2.6 software package (http://www.igipz.pan.pl/Bioklima-zgik.html). PET, UTCI, and SET were calculated using RayMan model (Matzarakis et al., 2007, 2010).

Table 1. The selected stations of northwest Iran

Station	Elevation (m)	Station	Elevation (m)
Ardabil	1,332	Parsabad	45
Ahar	1,391	Sagez	1,553
Jolfa	720	Sanandaj	1,373
Khoy	1,108	Tabriz	1,361
Mahabad	1,500	Tekab	1,765
Maku	1,411	Zanjan	1,663
Ourmieh	1,313	-	-

1. Equivalent Temperature
2. Wind Chill Temperature
3. Physiological Subjective Temperature
4. Subjective Temperature Index

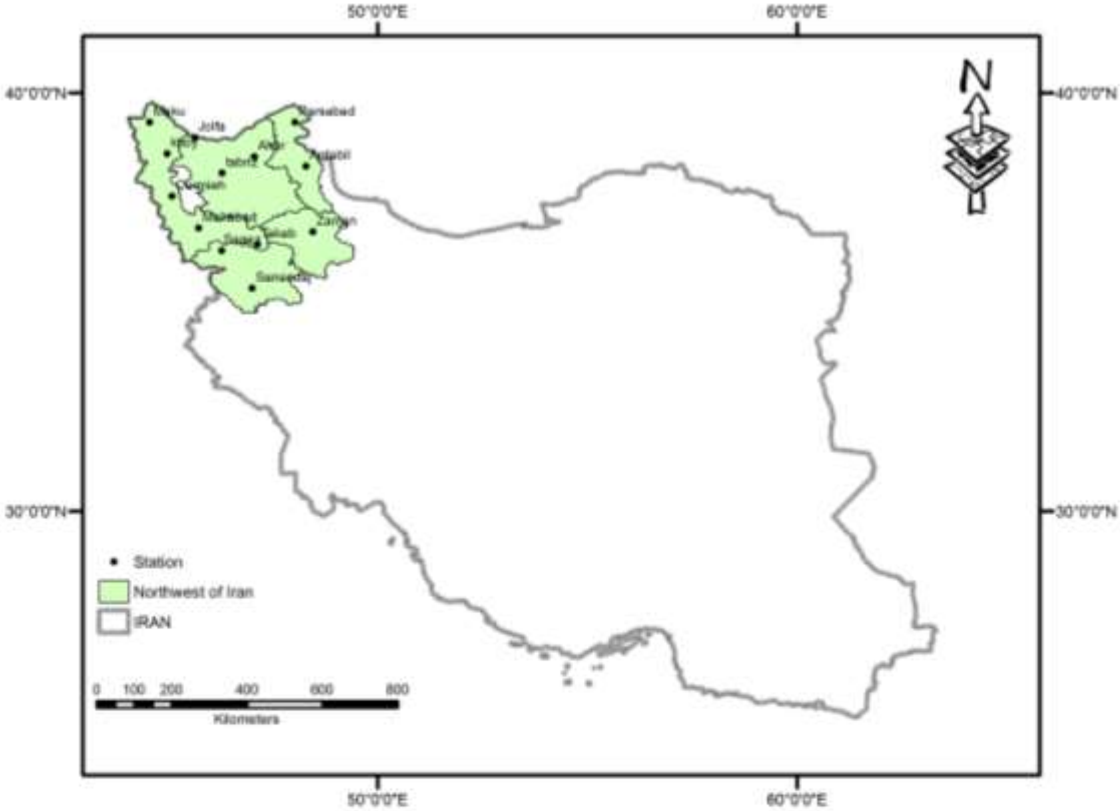


Fig. 1. The map of Iran and the selected stations

3. 1. Simple indices

This group of indices had two or three meteorological variables in the equation and did not indicate an area of thermal comfort thresholds; therefore, their results were not reliable. Because the parameters such as clothing insulation and metabolic rate were not considered in the evaluation of thermal comfort, in this study, the indices with unit scale of °C were used.

Equivalent temperature (TEK) was introduced by Dufton (1932, 1933), while Bedford (1951) described its use. TEK evaluates the common effect of air temperature and vapor pressure on human organism and is defined as a temperature required for air (in constant air pressure) if all its containing vapor was condensed. Effective temperature (ET) was first used within the community of occupational physiologists. Houghten and Yaglou (1923) introduced the effective temperature index (ET). This index was originally established to provide a method of determining the relative effects of air temperature and humidity on comfort. Missenard (1933) developed a mathematical formulation of effective temperature ("temperature résultante"). The index established a link between the identical state of the organism's thermoregulatory capacity (warm and cold perception) and differing temperature and humidity of the surrounding environment. The assessment of the effects of wind in cold environments on exposed skin areas has long been of great interest. Siple and Passel (1945) exposed snow-melted water in a plastic container to combine subfreezing environmental temperatures and wind speeds in the Antarctica. Wind chill index WCI (W m^{-2}) was calculated, expressing the cooling power of the wind in complete shade and without any evaporation, as is suggested in ISO TR 11079 (1993). This led to the development of wind chill temperature (WCT) (ASHRAE, 1997), which defines an equivalent environment of which the cooling power is identical to that of the actual, windy environment. Wet-bulb-globe-temperature (WBGT) was developed by the US Navy as part of a study on heat-related injuries during military training (Yaglou and Minard, 1957). The WBGT index, which emerged from the "corrected effective temperature" (CET) (Vernon and Warner, 1932) comprised the weighting of dry-bulb temperature, natural (un-aspirated) wet-bulb temperature, and black globe temperature. The Humidex is a Canadian innovation, which was first used in 1965 and was revised by Masterson and Richardson (1979).

It was devised by Canadian meteorologists to describe how hot- humid weather is felt by the average person. Assorted lists of indices are given in Table 2.

Table 2. The variables used to infer a thermal comfort quantity. T = air temperature (°C), VP and E = vapor pressure (hPa), RH= relative humidity (%), v = wind speed (m s^{-1})

Index	Input variables	Formula	Source
Equivalent temperature (TEK)	T, E	$TEK = T + 1.5 * E$	Dufton (1932, 1933) and Bedford (1951)
Effective temperature (ET)	T, RH, V	$ET = 37 - \frac{37 - T}{0.68 - 0.0014 * RH + \frac{1}{1.76 + 1.4V^{0.75}}} - 0.29 * T * (1 - 0.01 * RH)$	Houghten, Yaglou (1923) and Missenard (1933)
Wind chill temperature (WCT)	T, V	$WCT = 13.12 + 0.6215 * T - 11.37 * V_{10}^{0.16} + 0.3965 * T * V_{10}^{0.16}$	Falconer (1968)
Wet-bulb-globe-temperature (WBGT)	T, VP	$WBGT = 0.567 * T + 0.393 * VP + 3.94$	Yaglou and Minard, (1957)
Humidex	T, VP	Humidex = T + 0.5555 * (VP – 10)	Masterson and Richardson (1979)

3. 2. The indices derived from energy budget models

For the thermal evaluation of a specific location or area, not only is a single meteorological parameter required, but a complex evaluation of the effects of climate conditions and thermo-physiological values in order to describe the effects of the thermal environment on humans. Thermophysiological indices can be applied in different times and spatial resolutions to more recent climate and climate change projections (Gulyas and Matzarakis, 2007). In the present paper, the selected indices derived from different energy budget models were compared with the UTCI.

3. 2. 1. Physiologically equivalent temperature

PET is equivalent to the air temperature at which in a typical indoor setting (without wind and solar radiation) the heat balance of the human body (work metabolic rate of 80 W of light activity that should be added to the basic metabolic rate 86.5 W, Stolwijk and Hardy 1977; heat resistance of clothing 0.9 clo, which is the reference clothing insulation value used for the formulation of PET) is maintained with core and skin temperatures equal to those conditions under assessment (Mayer and Höppe, 1987; Höppe, 1999). The following assumptions were made for indoor reference climate: Mean radiant temperature was equivalent to the air temperature (Tmrt=Ta). Air velocity was set to 0.1 m/s. Water vapor pressure was set to 12 hPa (approximately equivalent to relative humidity of 50% at Ta=20°C). The PET assessment scale (Table 3) was derived by calculating Fanger's (1972) PMV for varying air temperatures in the reference environment, using the settings for the PET reference person (height: 1.75 m, weight: 75 kg, age: 35 years, and sex: male; work metabolic rate 80 W of light activity that should be added to the basic metabolic rate and heat resistance of clothing of 0.9 Clo) (Matzarakis et al., 1999). According to Höppe (1999), the assumption of constant values for clothing and activity in the calculation of PET was made in order to define an index independent of the individual behaviors.

3. 2. 2. Standard effective temperature

The (rational) standard effective temperature, SET is defined as the equivalent air temperature of an isothermal environment at 50% RH in which a subject, while wearing the standard clothing for the activity concerned, has the same heat stress (skin temperature T_{sk}) and thermoregulatory strain (skin wettedness, $_{w}$) as the actual environment. SET uses skin temperature and skin wettedness as the limiting conditions. The values for T_{sk} were derived from a two-node model of human physiology (Gagge 1971; Gagge et al. 1986). Table 3 presents the SET assessment scale.

3. 2. 3. Physiological subjective temperature and Subjective temperature

PST and STI indices are derived from the man environment heat exchange (MENEX) model which was first published in 1994 (Blazejczyk 1994). PST represents the subjective sensation persons in the thermal environment derives from signals of cold and/or warm receptors in the skin and in the nervous system. Thermal effects of the environment are expressed through mean radiant temperature formed under clothing (innerTmrt). PST is defined as the temperature formed around the skin surface, under clothing, after an interval of 15–20 min of adaptation to maintain homeothermy. PST indicates the effect of environmental factors and of specific physiological responses to the thermal stimuli. It is applicable in a wide range of environmental conditions, although this index is limited to wind speeds lower than 22 m s^{-1} (Blazejczyk et al., 2012).

STI is an index that illustrates the thermal load subjectively felt by an individual, which results from the ambient environment before the activation of adaptation processes. It depends on both ambient conditions (temperature, solar radiation, wind, and humidity) and the heat exchange in the individual's environment. STI represents the thermal load formed in the air layer surrounding the outer layer of clothing. The thermal impacts of environment are expressed by means of radiant temperature (Mrt). The physiological response of an organism is represented by the net heat storage (S) (Blazejczyk, 2005). The range of the indices and its comfort values are presented in Table 3.

3. 2. 4. Universal thermal climate index

The Universal Thermal Climate Index (UTCI) is defined as an equivalent ambient temperature (°C) of a reference environment, providing the same physiological response of a reference person as the actual environment (Weihs et al., 2012). The calculation of the physiological response to the meteorological input is based on a multi-node model of human thermoregulation (Fiala et al., 2001), which is associated with a clothing model. Table 3 presents the UTCI assessment scale. This assessment scale is based on different combinations of rectal and skin temperatures, sweat rate, shivering, etc., which might indicate ''identical'' strain resulting in non-unique values for single variables like rectal or mean skin temperature in different climatic conditions having the same value of UTCI (Błazejczyk et al., 2012). Static clothing insulation, when adjusted to the ambient temperature, taking into consideration the seasonal clothing adaptation habits of Europeans, has a notable effect on the human perception of the outdoor climate (Havenith et al., 2012).

4. Results and Discussion

4. 1. Regression analysis between of UTCI in comparison to thermal indices

The comparison between UTCI and simple meteorological parameters such as air temperature (T), mean radiant temperature (Tmrt), and dew point temperature (Td) showed that there was a high correlation between Tmrt and UTCI. The R^2 was almost 81%, and the slope coefficient was 0.90. For T and Td the slope coefficient of the regression line and R^2 were similar (R=0.88 and R^2= 77%).

Figure 2 shows the statistical relationships between UTCI and the simple thermal indices (WBGT, Humidex, TEK and WCT). It is evident that there was a rather weak correlation between the indices and UTCI. R^2 values were relatively low, with values between 76% - 86%. The regression lines of the indices were farther apart from the lines of identity, with an exception to the ET index which had an R^2 of 0.95 and a regression line close to the line of identity (Table 4). Simple indices (TEK, WBGT and Humidex) experienced a relatively weak correlation with UTCI, with corresponding low R^2 coefficients. The regression lines also differed significantly from the lines of identity. The slope coefficients were moderate to high (0.87– 0.88). The weak similarity experienced between simple indices and UTCI resulted from

Table 3. Temperature thresholds (°C) of particular thermal sensations (of alert descriptions) used in various thermal indices

	Indices derived from energy budget models					Simple indices				
Index / Thermal sensation	UTCI	PET	SET	STI	PST	TEK	ET	WCT	Humidex	WBGT
Extreme cold stress	< -40	-	-	-	-	-	-	-	-	-
Frosty (extreme hazard)[a] (Very strong cold stress)[C]	-27 to - 40	-	-	< -38	< -36	-	< 1	< -55	-	-
Very cold (very cold)[a] (Strong cold stress)[C]	-13 to -27	< 4	-	-38 to -20	-36 to -16	< 18	< 1	-54 to -40	-	-
Cold (cold)[a] (Moderate cold stress)[C]	0 to-13	4-8	-	-20 to -0.5	-16 - 4	18-24	1-9	-37 to -28	-	-
Cool (moderate hazard)[a] (Slight cold stress)[C]	9 to 0	8-18	< 17	-0.4-22.5	4-14	24-32	9-17	-27 to -10		-
Comfortable (no danger)[a],[b] (No thermal stress)[C]	+9 to +26*	18-23	17-30	22.5-32	14-24	32-44	17-21	> - 10	< 30	< 18
Warm (caution)[b] (Moderate heat stress)[C]	+26 to +32	23-35	30-34	32-46	24-34	44-56	21-23	-	30-40	18-24
Hot (extreme caution)[b] (Strong heat stress)[C]	+32 to +38	35-41	34-37	46-55	34-44	> 56	23-27	-	40-45	24-28
Very hot (danger) [b] (Very strong heat stress)[C]	+38 to +46	> 41	> 37	55-70	44-54	-	> 27	-	45-55	28-30
Sweltering (extreme danger)[b] (Extreme heat stress)[C]	> +46	-	-	> 70	> 54	-	-		> 55	> 30

[a] Alert descriptions for WCT and TEK [b] Alert descriptions for Humidex and WBGT and [C] Alert descriptions for UTCI

* It can be noted that, with respect to the averaged dynamic thermal sensation, UTCI values between 18°C and 26°C may comply closely with the definition of the 'thermal comfort zone' supplied in the Glossary of Terms for Thermal Physiology (IUPS 2003) as: The range of ambient temperatures, associated with specified mean radiant temperature, humidity, and air movement, within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period.

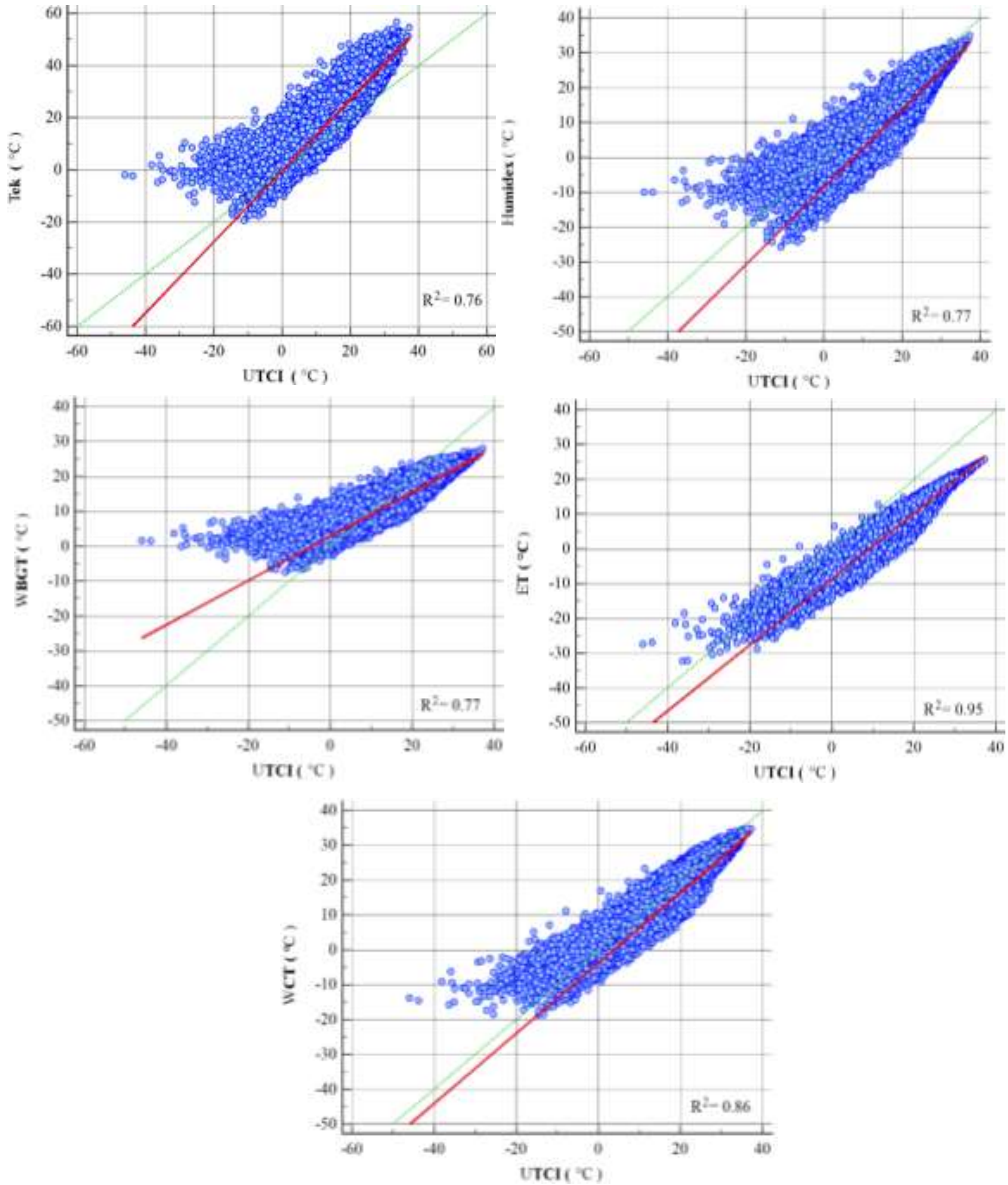


Fig. 2. Linear regression between UTCI and simple thermal indices of TEK, Humidex, WBGT, ET, WCT. Red dashed line shows Regression, green dashed line shows identity

their philosophy; they combined, in a very simple way, only two meteorological variables (i.e., air temperature and humidity). None of them included solar radiation. A comparison of ET and WCT with UTCI exhibited high and good correlation. For ET, R was almost 0.97, and for WCT, it was 0.93. R^2 coefficients were significant (95% and 86%, respectively).

The values most similar to those of UTCI were found in the indices derived from human energy balance models (i.e., PET and SET). These two indices were of similar approach to UTCI, in other words, they indicated equivalent temperature. The differences in specific values resulted from the various structures of energy balance models and different definitions of reference conditions. STI and PST exhibited relatively weak correlation with UTCI (Table 4 and Fig. 3).

Table 4. Descriptive statistics of temperature differences and correlation coefficient (R) between (UTCI) and selected indices in northwest of Iran, during the period 1986–2007

Index	Min	Max	Average	Variance	R
Physiologically equivalent temperature (PET)	-32.6	6.4	- 0.1	16.9	0.95
Standard effective temperature (SET)	-25.7	3.9	- 0.7	8.8	0.97
Subjective temperature index (STI)	-41.4	18.9	-15.4	127.4	0.83
Physiological subjective temperature (PST)	-51.9	23.2	1.7	97.8	0.87
Wind chill temperature (WCT)	-32.2	12.4	2.7	19.2	0.93
Humidex	-36.1	18.2	5.4	33.1	0.88
Wet-bulb-globe-temperature (WBGT)	-47.7	10.8	2.0	44.2	0.88
Equivalent temperature (TEK)	-44.0	10.9	-6.9	48.9	0.87
Effective temperature (ET)	-18.6	17.5	6.8	8.0	0.97
Temperature (T)	-	-	-	-	0.88
Dew point temperature (Td)	-	-	-	-	0.88
Mean radiant temperature (Tmrt)	-	-	-	-	0.90

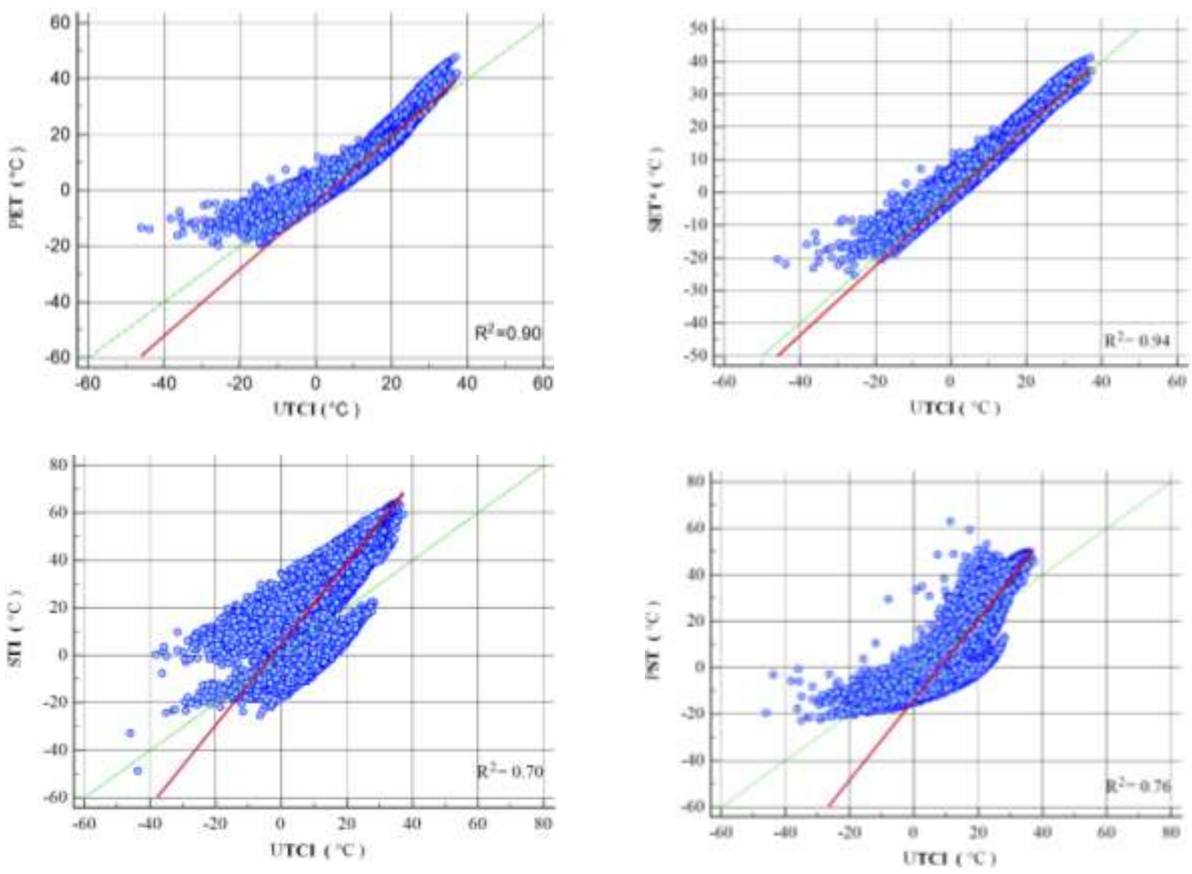


Fig. 3. Linear regression UTCI to indices derived from energy budget models. PET, SET*, STI, PST. Red dashed line shows Regression, green dashed line shows identity

The group of indices based on the human heat balance exhibited a high correlation with UTCI. The best results were obtained for SET (adapted for outdoor conditions). Both R^2 coefficient (94%) and the coefficient of the slope of the regression line (a= 0.97) were best for this group of indices. This may result from the low clothing insulation in SET, which coincided with the relatively low values of UTCI in case of higher wind speeds. High correlation and good slope parameters were also found for PET. It is noteworthy here that the values of SET and PET changed gradually because of the changes of UTCI over the whole temperature range. The value of PET did not fall below −20°C, however, UTCI value fell below −46°C. For PET, the lowest value was about −19.8°C, while UTCI value varied from +37 to −46°C. The variation experienced in PET increased with decreasing UTCI, due to their fixed clothing insulation under cold conditions, compared with the season, especially, the wind dependent clothing insulation of UTCI. R^2 coefficient was 90%. In contrast to PET, the variation in PST increased with increasing UTCI. One exception to this was the STI index because this index had relatively weak correlation with UTCI (Table 4 and Fig. 3).

The difference between UTCI and the other indices was clearly observed while comparing the distribution of the residuals (dT= UTCI−any index) (Blazejczyk et al., 2012). In all cases, the range of the residuals was very wide. The weakest agreement was observed with PST. UTCI value can be up to−52°C lower and 23°C higher than PST. Relatively maximum dT ranges were found for PST, STI and humidex. SET and PET experienced a symmetrical difference range which differed from UTCI, with mean values of −0.7 to -0.1°C. However, this variation was in better to SET than the PET index. Considering all the statistics of dT, it can be concluded that the best conformity with UTCI is seen with the SET and PET indices (Table 4).

4. 2. Comparison ET, PET and SET indices with UTCI based on Bland and Altman plot

ET index showed the best compliance with UTCI. However, to have a more dependable basis, the obtained results were analyzed using Bland and Altman plot. The analysis of this plot between UTCI and ET (Figure 4) indicated similar linear and mean difference of 6.8°C, with ranges of agreement between -1.8°C to 15.3°C. The precision was 94%, which confirmed the strong linear relationship between the two indices. The accuracy represented a bias correction factor, which measured the deviation of the best-fit line from the 45° line through the origin. In the present study, the accuracy was 81%.

Based on the results, PET and SET indices showed the best compliance with UTCI. For a more accurate assessment of this result, Bland and Altman plot was used. The analysis of this plot between UTCI and PET (Figure 5) indicated similar linear and mean difference of -0.1°C, with ranges of agreement between -13.1 °C to 12.8 °C. The precision was 97%, which confirmed the strong linear relationship between both indices. The accuracy represented a bias correction factor, which measured the deviation of the best-fit line from the 45° line through the origin. In the present study, the accuracy was 99.99%.

The analysis of Bland and Altman plot between UTCI and SET (Figure 5) indicated similar linear and mean difference of -0.7°C, with ranges of agreement between -5.7 °C to 4.3 °C. The precision was 97%, which confirmed the strong linear relationship between both indices. The accuracy represented a bias correction factor, which measured the deviation of the best-fit line from the 45° line through the origin. In this study, the accuracy was 99.80%.

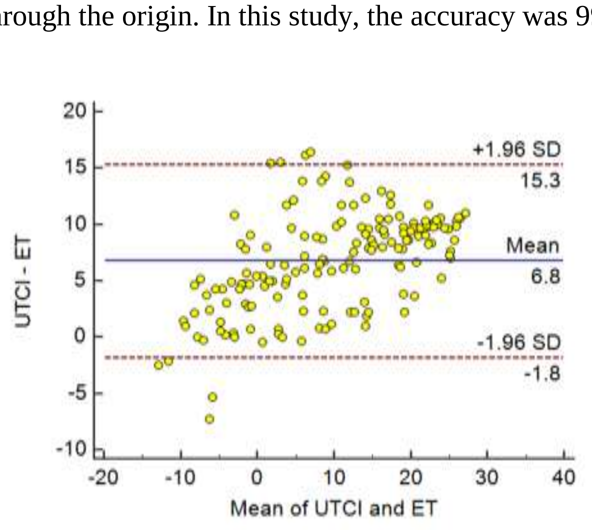
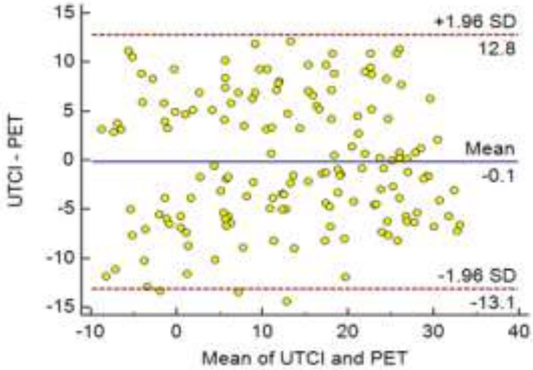


Fig. 4. Bland-Altman plot showing the difference between UTCI and ET



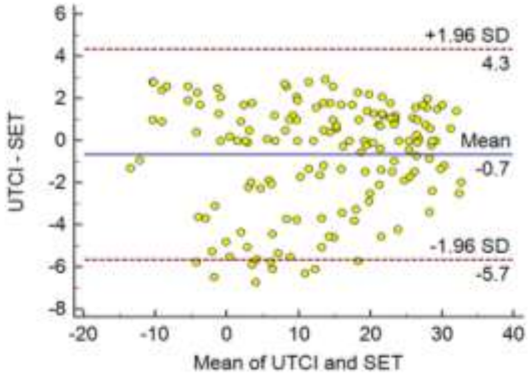


Fig. 5. Bland-Altman plot showing the difference between UTCI and PET (Left panel) UTCI and SET (Right panel)

4. 3. Frequency of various ranges of differences thermal index minus air temperature

The general statistics for the data from northwest of Iran illustrated how particular indices differed from air temperature. Two analyses were performed. The first analysis involved the calculation of the differences between studying thermal indices and air temperature (dT*) and their grouping into 5 K dT* ranges (Table 5). The second analysis compared the frequency of particular classes of indices. In the case of UTCI, the values varied from ambient temperature *T* within a very wide range, from −14 K to +13 K. However, majority of dT* values represented the range of between −10 to +10 K. In general, UTCI provided values rather lower than the air temperature with a noticeable asymmetric distribution. For WBGT, Humidex, and WCT the majority of values only slightly differed from T (from −5 to +10 K). This suggests that, for this group of indices, their values depended mostly on ambient temperature. STI and TEK values were usually higher than T. However, PET, SET, and ET indices provided values lower than air temperature (Table 5).

Table 5. Frequency of various ranges of differences in thermal index minus air temperature (dT*), northwest of Iran, during the period 1986–2007

DT*	PET	SET	PST	STI	WBGT	Humidex	WCT	ET	TEK	UTCI
-25: -20	0	0	0	0	0	0	0	0	0	0
-20: -15	0	0	0	0	0	0	0	0	0	0
-15: -10	0	4.5	0	0	0	0	0	3.3	0	1.9
-10: -5	*43.6*	*34*	*4.5*	*0*	*0*	*0.6*	*0*	*78.1*	*0*	*28.2*
-5: 0	*9*	*17.9*	*42.3*	*0*	*26.3*	*71.2*	*35.9*	*18.6*	*0*	*24.4*
0: 5	*39*	*25*	*16.7*	*0*	*55.1*	*24.4*	*64.1*	*0*	*1.9*	*19.2*
5: 10	*8.4*	*16.7*	*12.8*	*0*	*18.6*	*3.8*	*0*	*0*	*39.7*	*21.8*
10: 15	0	1.9	11.5	0.6	0	0	0	0	30.1	4.5
15: 20	0	0	10.3	16.7	0	0	0	0	16	0
20: 25	0	0	1.9	26.3	0	0	0	0	7.1	0
25: 30	0	0	0	28.2	0	0	0	0	1.3	0
30: 35	0	0	0	26.3	0	0	0	0	2.6	0
35: 40	0	0	0	1.9	0	0	0	0	1.3	0
Max	8.2	13.0	21.5	36.9	7.2	8.3	2.3	-2.3	37.5	12.8
Min	-8.6	-12.3	-6.5	14.0	-4.5	-5.6	-2.6	-13.5	-0.0	-13.6
Average	-1.8	-1.4	3.9	26.0	2.1	-0.9	0.7	-6.5	12.6	-0.3
Variance	4.9	6.1	7.5	5.3	2.8	2.5	1.0	1.9	6.6	6.4

* Source: Błazejczyk et al. 2012

4. 4. Mean analysis (1986–2007) selected thermal indices in northwest of Iran

Table 6 lists the results of a descriptive analysis of selected simple indices. According to the table, TEK index had the highest value. The minimum and maximum annual TEK occurred in Mahabad (0˚C and 62.5˚C). Mean annual TEK values in most of the stations with the exception of Jolfa, Khoy, Mahabad, and Parsabad were lower than the overall average (24.9˚C). The lowest and highest annual mean ET occurred in Tekab (18.8˚C) and Parsabad (34.4˚C), respectively. Annual ET values in the stations of Jolfa, Khoy, Mahabad, Ourmieh, Parsabad, Sagez, and Sanandaj were higher than the overall average (6.2˚C). The lowest and highest annual mean ET occurred in Ardabil (1.5˚C) and Khoy (9.2˚C). The minimum and maximum annual ET occurred in Ahar (-11.7˚C) and Parsabad (21.6˚C), respectively. Highest mean WCT (16.2˚C) occurred in Parsabad while the the lowest (9.3˚C) occured in Ardabil. The minimum and maximum annual WCT occurred in Tekab (-3.8˚C) and Jolfa (31.4˚C), respectively. In Humidex index, the minimum and maximum annual occurred in Tekab and Mahabad (-7.7˚C and 33.3˚C), respectively. Mean annual Humidex in more than 60% of stations was lower than the overall average (11.2˚C). The lowest and highest mean annual Humidex occured in Tekab (7.2˚C) and Parsabad (16.7˚C), respectively. In WBGT index, the mean annual in more than 60% of stations was lower than the overall average (14.1˚C). Tekab station exhibitedthe lowest annual mean (3˚C) while Mahabad station exhibited the highest annual mean (27.9˚C).

Generally, according to Table 6, the lowest values of the indices occurred in Tekab while the highest values occurred in Mahabad and Parsabad. The largest values of the variation (standard deviation) in TEK showed that the variations were between 12.4˚C to 22.7˚C. In contrast to the lowest values of the variation, WBGT indicated that the variations were between 6˚C to 8.7˚C.

Table 7 represents the results of a descriptive analysis derived from energy budget models. According to this table, STI index had the highest values. The minimum and maximum annual STI occurred in Parsabad and Tabriz (61.9˚C and 3.2˚C), respectively. Mean annual STI values in 54% of stations were lower than the overall average (34.1˚C). The lowest and highest mean annual PST occurred in Ardabil (6.9˚C) and Jolfa (21.4˚C). Also, the minimum and maximum annual PST occurred in Tabriz (-8.9˚C) and Parsabad (47.2˚C), respectively. The values of the three indices PET, SET, and UTCI were almost similar, with an overall mean value of almost 13˚C. The mean annual PET and SET values in the stations of Ahar, Ardabil, Mahabad, Maku, and Tekab were lower than the overall average (1˚C). The highest mean of PET and SET (21˚C) occurred in Khoy while Tekab station exhibited the lowest (7˚C) mean. However, in UTCI index, the highest mean (16.9˚C) occurred in Khoy, while Ahar station displayed the lowest (7.9˚C) mean. The minimum and maximum annual of PET, SET, and UTCI occurred in Ahar and Khoy, respectively.

The largest values of variation (standard deviation) in PST occurred between 11.4˚C to 19.1˚C. In contrast to the lowest values of the variation, PET values occured between 8.7˚C to 12.8˚C. In addition, it can be inferred from Table 7 that PET, SET, and UTCI exhibited similar values.

4. 5. Monthly changes of UTCI and selected thermal indices

Figure 6 shows the changes of UTCI in comparison to simple thermal indices. A comparison of UTCI with the simple indices indicated that ET and WCT indices were closest to UTCI values. Both indices exhibited the best correlation with UTCI. According to this Figure, ET and WCT values were close to UTCI, especially in the summer. During sunny days, simple indices did not illustrate the impact of solar radiation compared to UTCI. Among the simple indices, the values of TEK were higher than UTCI. As illustrated in Figure 2, TEK had the lowest of conformity to UTCI. When comparing ET and WCT with UTCI, a significant conformity among their values was observed. For ET, R^2 was 94, and for WCT, it was 86. In most cases and in majority of the stations, these three indices demonstrated similar changes in their values (Table 6).

Figure 7 shows monthly changes of UTCI derived from energy budget models in the northwest of Iran during the period 1986–2007. When comparing UTCI with other indices, a significant conformity between SET and PET was the closest indices to UTCI. This conformity was clearly evident in the warmer months. In all stations, these three indices demonstrated

Table 6. Descriptive statistics selected simple indices for the examined sites in the northwest of Iran during the period 1986–2007

Index		Ahar	Ardabil	Jolfa	Khoy	Mahabad	Maku	Ourmieh	Parsabad	Sagez	Sanandaj	Tabriz	Tekab	Zanjan	Overall mean
TEK	Mean	22.8	22.4	28.7	26.3	32.2	21.5	23.6	34.4	23.2	24.8	23.4	18.8	22.1	24.9
	SD	13.5	13.8	16.3	15.9	22.7	14.3	14.6	16.9	13.9	12.8	14.1	12.4	13.7	15
	Minimum	5.1	3.3	5.8	4.1	0	1.7	3.4	13.1	3.3	6.5	3.3	1.2	2.8	4.1
	Maximum	41.8	40.9	50.9	48.9	62.5	41.7	44.4	58.2	43.1	42.9	42.6	36.8	41.6	45.9
ET	Mean	2.9	1.5	9	9.2	7.8	4.9	6.7	9	7.1	8.6	5.3	2.6	5.9	6.2
	SD	10	8.4	9.6	9	9.5	9.3	8.8	9.4	9.6	9.4	10.1	9.3	9.7	9.4
	Minimum	-11.7	-10.5	-5.5	-4.2	-3.3	-7.9	-5.9	-3.1	-6.5	-4.5	-9.4	-10.5	-8.6	-7
	Maximum	15.3	12	21.4	21.1	21.3	17.4	18.6	21.6	20.1	21.6	18.4	15.4	18.4	18.7
WCT	Mean	10.9	9.3	16.2	14.5	13.7	11.4	12.6	16.2	13.6	15.6	13	9.9	12.6	13
	SD	9.5	8.4	11.2	9.9	9.9	10.1	9.6	9.5	10.7	10.8	11	9.9	10.4	10.1
	Minimum	-2.5	-2.9	0.2	0	-0.1	-2.6	-1	4.1	-1.3	0.9	-2.5	-3.8	-2.3	-1.1
	Maximum	23.2	19.9	31.4	28	27	25.2	25.7	29.3	28.4	31.2	27.9	23.8	26.4	26.7
Humidex	Mean	9.7	8.4	14.4	12.1	14.5	9	10.2	16.7	10.7	12.6	10.8	7.2	9.8	11.2
	SD	10.2	10	12.7	12.1	14.1	11.4	11.3	11.8	11.7	11.2	11.7	10.6	11.3	11.5
	Minimum	-4	-6	-3.7	-5.3	-5.6	-7.1	-5.9	1.7	-6	-3.3	-5.9	-7.7	-6.3	-5
	Maximum	23.6	21.5	31.5	28.8	33.3	24.6	25.9	33.1	27	28.5	26.6	22.1	25.3	27.1
WBGT	Mean	13.2	12.6	16	14.6	16.3	12.8	13.5	17.6	13.7	14.8	13.8	11.7	13.2	14.1
	SD	6.1	6	7.5	7.2	8.7	6.7	6.7	7.1	6.8	6.5	6.8	6.1	6.6	6.8
	Minimum	5.1	4	5.3	4.4	3.9	3.3	4.1	8.5	4	5.6	4.1	3	3.8	4.5
	Maximum	21.5	20.4	26.1	24.6	27.9	22	22.8	27.5	23.3	24	23	20.4	22.3	23.5

SD is the standard deviation of the monthly averages from 1986 to 2007.

Table 7. Descriptive statistics of selected indices for the examined sites in the northwest of Iran during the period 1986–2007

Index		Ahar	Ardabil	Jolfa	Khoy	Mahabad	Maku	Ourmieh	Parsabad	Sagez	Sanandaj	Tabriz	Tekab	Zanjan	Overall mean
PET	Mean	7.4	9.8	13.4	20.5	11	8.6	15.6	13.8	17.3	18.1	13.3	6.4	15.1	13.1
	SD	10.7	8.7	12.4	11.7	12.8	12	10.4	11	11.2	11.3	11.1	11.4	11.4	11.2
	Minimum	-8.8	-2.8	-7	3.5	-8.6	-10.4	0.7	-2.4	1.8	3	-2.9	-11.3	-1.4	-3.6
	Maximum	22	20.3	30.1	36.4	29.4	25.6	30	29.6	33.4	34.6	27.9	22.3	29.9	28.6
UTCI	Mean	7.9	9.4	15	16.9	13.2	10.9	14.6	16.3	16.3	16.1	10.7	8.6	12.8	13
	SD	13.3	10.4	11.4	11.1	14.1	12.2	10.8	10.8	9.9	11.8	12.4	11.8	12.1	11.7
	Minimum	-14.2	-5.9	-4.2	0.5	-9.9	-7.9	-1	-0.1	1.8	0.2	-7.2	-9	-4.8	-4.7
	Maximum	23.9	21.2	28.6	31.7	30.9	26.4	29.2	30	29.7	32.7	26.8	23.7	28.4	27.9
SET	Mean	7.3	10.9	13.8	21.2	11.5	9.4	14.6	14.5	17.9	18.7	14.3	7	16.1	13.6
	SD	12.5	9.1	12.1	9.7	13.8	12.6	10.8	11	9.6	9.3	10.2	12.3	10.3	11
	Minimum	-12.9	-2.3	-6.8	6.4	-10.9	-10.3	-1	-2.6	4	5.3	-1.5	-11.8	0.5	-3.4
	Maximum	22.9	21.5	28	33.7	29.2	25.3	29.2	28.5	30.9	31.3	26.7	22.9	28.7	27.6
STI	Mean	35.9	24.1	40.7	32.4	40.7	36.5	31.2	42.8	31.6	33.3	28.3	35	30.5	34.1
	SD	14.4	14	14.8	18.4	17.1	14.9	17.9	14.7	18.5	17.6	17.6	13.3	17.4	16.2
	Minimum	15.1	6.3	17.8	6.8	14.1	15	5.6	22.1	5.9	9.3	3.2	15.8	6.7	11
	Maximum	53.9	43.9	58	57.6	61.8	56.1	55.7	61.9	56.6	56.9	51.1	53.2	53.8	55.4
PST	Mean	12.2	6.9	21.4	16.5	18.5	14.4	13.6	21	15.3	17.2	13	11.9	13.5	15
	SD	15.2	11.4	18.8	18	18.5	15.8	16.9	17.7	18.7	19.1	19	14.3	17.6	17
	Minimum	-6.7	-7.1	-2.5	-5.6	-4.2	-4.3	-6.6	-0.1	-6.7	-5	-8.9	-4.7	-7.3	-5.4
	Maximum	34.1	24.4	47.2	43.5	46.5	39	40.1	45.7	43.5	45.1	41.9	35.3	39.8	40.5

SD is the standard deviation of the monthly averages from 1986 to 2007.

similar changes in their values. According to Figure 7, PET and SET values were very close to UTCI, especially in the summer. Additionally, the two indices illustrated clearly the changes in thermal conditions due to fluctuations in wind speed. One exception was STI index. Its values were significantly higher than the other indices. Also in the warm months, PST values were higher than UTCI (Table 7).

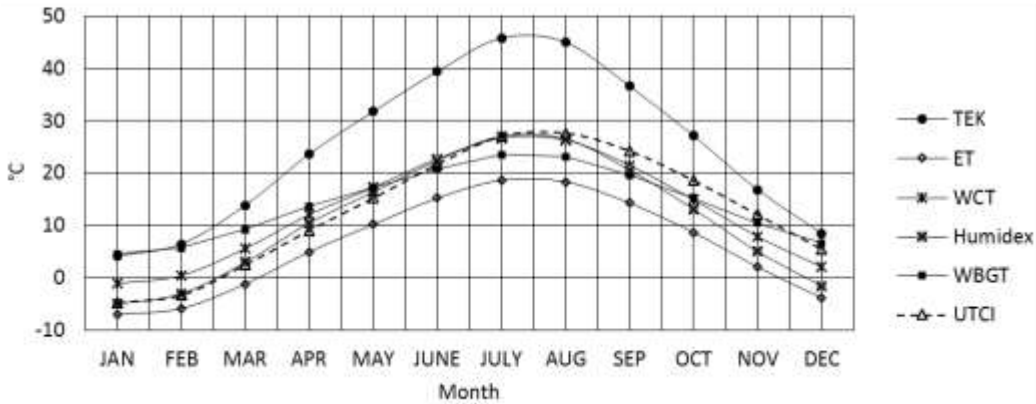


Fig. 6. Monthly changes of UTCI and simple indices in the northwest of Iran during the period 1986–2007

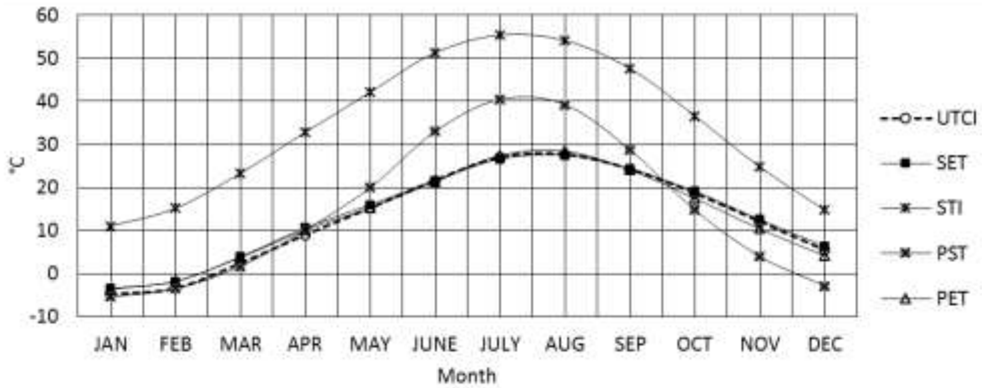


Fig. 7. Monthly changes of UTCI and other indices in the northwest of Iran during the period 1986–2007

4. 6. Assessment classes of UTCI and classes of thermal sensations defined by other indices

To analyze the 22-year (1986-2007) database from the northwest of Iran, the frequency of particular assessment classes of UTCI was compared with those of other indices (Fig. 8). In this region, UTCI values represented four classes of the possible ten categories of heat/cold stress, while the other indices showed seven out of the maximal nine categories (Table 3). According to the definition in Table 3, in the present study, the number of categories was restricted to seven for PET and five for SET. In the study area, extreme cold stress occurred in some stations on several occasions. However, there was no observed extreme heat stress. The most frequent was synoptic situations which varied from moderate cold stress to moderate heat stress. A similar range of conditions was also reported by the PST and TEK indices. However, the proportions between particular classes of thermal sensations differed from UTCI; PST indicated a higher frequency of cold conditions than UTCI. ET, TEK, and PET classes of thermal sensations gradually moved significantly to cold and very cold, which, at least for PET, was due to an assessment related to a typical indoor setting concerning clothing insulation and activity. However, SET indicated milder conditions than UTCI and the other indices (Fig. 4), whereas the lowest SET category was “cool” and the highest STI and PST category was “very hot” (Table 3).

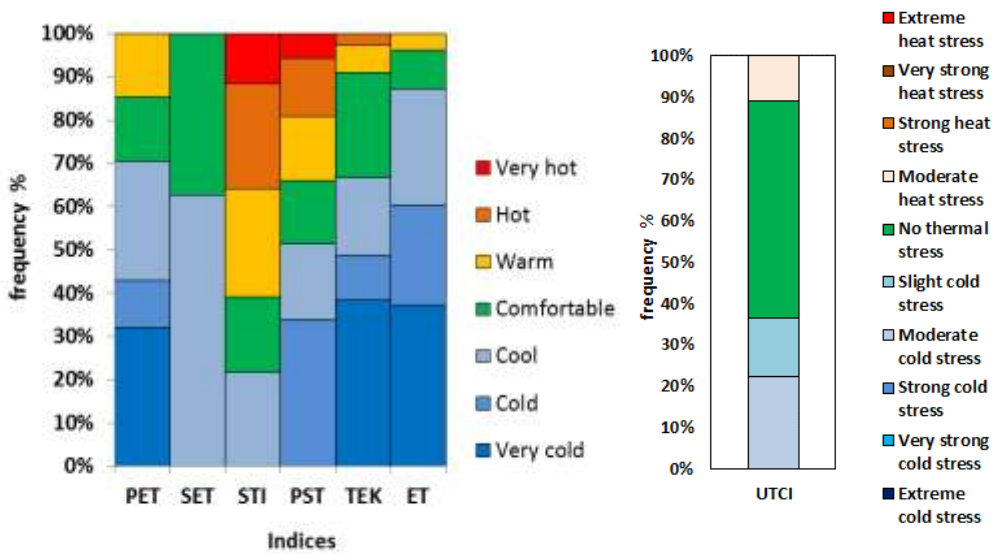


Fig. 8. Frequency of particular assessment classes of UTCI (Right panel) and classes of thermal sensations defined by other indices in northwest of Iran during the period 1986 – 2007

Based on the aforementioned discussion, it could be said that in the assessment scales of the indices (Table 3), a high correlation existed between the temperature values of the indices independent from the assumptions regarding metabolic rate and clothing insulation. This was not surprising because most of the equivalent temperatures related to complete energy budget models (e.g., PET, SET) were obtained by solving the energy budget equation for the actual and reference environments for unchanged metabolic rate and clothing insulation.

4. 7. Changes in annual mean of UTCI

Figure 9 illustrates the variation in the annual UTCI index in the northwest of Iran during the period 1986–2007. From the temporal–spatial perspective the lowest rate of UTCI (-33)°C in Sagez station occurred in February, 1989, while the highest rate of UTCI (+36)°C occurred in Mahabad station in July, 2000. According to Figure 5, it is evident that UTCI index is a very good indicator to describe the living conditions of climate warming during the year. The result of the UTCI tests has shown that this index is suitable for the description of thermal comfort conditions during the warm period of the year and especially during sunny days. A course of the UTCI is also useful during cold days, but there is, a very strong influence in windy conditions. A rapid decrease in the values of UTCI was observed when the wind speed increased. UTCI index reflected the effect of a variety of meteorological variables on the heat balance human body in a thermo-physiologic manner similar to PET index. Thus, the index enables the transformation of a general meteorological information into an evidence for human-biometeorological applications (e.g., for assessing tendencies to heat load or to cold stress).

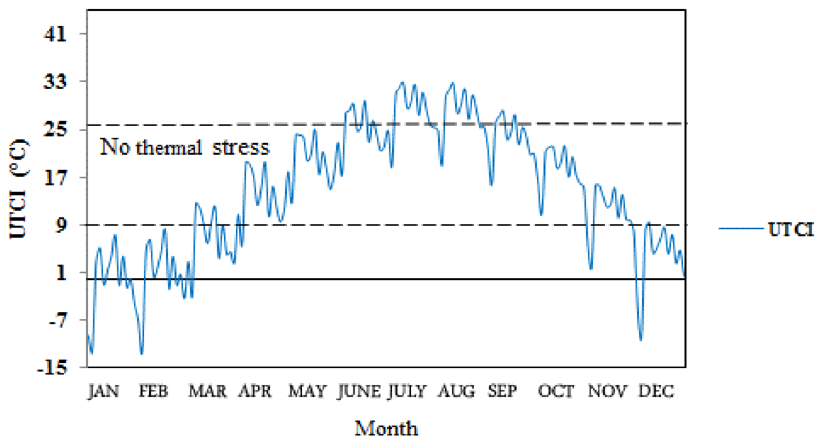


Fig. 9. Annual of regional averaged UTCI index in the northwest of Iran during the period 1986–2007

5. Conclusions

This study is the first case study that compared UTCI index with some selected thermal indices in the northwest of Iran. The results indicated that ET exhibited a good relationship with UTCI because the three components, wind speed, air temperature, and relative humidity were used in this index. On the other hand, ET exhibited noticeabe sensitivity to the cooling effect of the wind. Among the thermo-physiological indices, PET and SET demonstrated very strong correlation with UTCI. For the indices of STI, PST, TEK, WBGT, and Humidex, the correlation with UTCI was relatively weak. The weakest agreement was observed with STI. These findings agreed with the results of Błazejczyk et al. (2012) who concluded that the values for the indices derived from human heat balance models (i.e., PET and SET) were most similar to those of UTCI because these indices indicated equivalent temperature.

According to the Bland and Altman plot, high correlation was found among PET, SET, and UTCI so that the accuracy and precision of these indices was more than 95%. PET, SET, and UTCI values were are similar in almost all stations. The overall average of these indices was almost 13˚C. The lowest and highest annual mean, the minimum and maximum annual PET, SET, and UTCI demonstrated showed similar patterns in the stations (Ahar, Khoy, and Tekab).

The results of this present research is to an extent in conformity with the results from previous studies conducted in recent years. Several indices (THI, WBGT, PET, and UTCI) were evaluated to examine the applicability of using these indices in the arid environment by Shady (2013), which indicated that both PET and UTCI could be used successfully for the arid environment to evaluate the thermal sensation and heat stress, and their results were almost similar. Bröde et al. (2013), by evaluating the three indices of UTCI, WBGT, and PHS to these results, concluded that UTCI was sensitive to humidity and radiation in warm environments, as well as to wind speed in cold climates. This index has the potential to provide a valid and easy-to-use assessment of the physiological response to both cold and heat stress. The findings of this study showed a rapid drop in the values of UTCI when wind speed was increased. This was in accordance with the results of Novak (2013) and Nowosad et al. (2013), that UTCI index reflected the impact of a variety of meteorological variables on the heat balance of human body in a thermo-physiologic manner similar to PET index. Thus, this index enables general meteorological information to be transformed into an evidence for human-biometeorological applications (e.g., for assessing tendencies to heat load or to cold stress).

The lowest value of UTCI (-33)°C occurred in Sagez station while the highest amount UTCI (+36)°C occurred in Mahabad station; this was due to their fixed clothing insulation under cold conditions compared with the season and, especially, the wind dependent clothing insulation of UTCI. Similar results to the results of this research were obtained by Błazejczyk et al. (2012) and Bleta et al. (2014).

Owing to the high correlation among UTCI, PET, and SET, these indices were able to show the most suitable conditions for the thermal comfort environment, while UTCI index proved that it was suitable for the description of human comfort conditions during the warm period of the year, especially during sunny days. A course of UTCI was also useful during cold days, but there was a special event in windy conditions. A repid decrease in the values of the UTCI was observed when wind speed increased. Based on the findings of this study, it can be concluded that the indices derived from energy budget models in cold and warm periods of the year are better indicators of thermal comfort conditions than simple indices. Generally, the results of this study are useful for native people and as a guide to tourists or visitors in understanding thermal comfort, planning outdoor recreational activities, and developing the tourist industry.

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