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Evaluation of human thermal comfort using UTCI index: case study Khorasan Razavi, Iran

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Abstract

The Universal Thermal Climate Index (UTCI) addresses these shortcomings by using an advanced thermo-physiological model. The aim of this study was to investigate and prepare zoning of thermal comfort condition using UTCI. Meteorological data including temperature, wind speed, cloudiness and relative humidity were obtained on a daily time scale from 10 synoptic stations during (2004-2013) period. For the calculation of UTCI index Ryman and Bioklima softwares were used. Then the relationship between UTCI and elevation was investigated and by using Digital Elevation Model (DEM), UTCI zoning was prepared. The results showed that there is a strong inverse relationship between UTCI and elevation. Spatial and temporal zoning maps showed the highest values of UTCI were observed in the northeastern part of province (Sarakhs station) on July. In the cold months the lowest values of UTCI has been recorded in January. Extreme heat stress was observed across the East, South and South-East of Khorasan Razavi province. While cold stress has been more dominant In the Central and northern areas of the province. Generally there is a significant correlation between the thermal comfort and elevation, so that thermal stresses are often observed in the low regions in the warm period of the year.

Keyword

Khorasan Razavi, thermal stress, UTCI.

Abbreviation

UTCI: Universal Thermal Climate Index
DEM: Digital Elevation Model
PET: Physiologically Equivalent Temperature
MEMI: Munich Energy-Balance Model for Individuals
PT: Perceived Temperature
ISB: International Society of Biometeorology
COST: Cooperation in Science and Technical Development
Mrt: Mean radiant temperature

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RH: Relative Humidity
MCS: Moderate Cold Stress
SCS: Slight Cold Stress
NTS: No Thermal Stress
MHS: Moderate Heat Stress
SHS: Strong Heat Stress

1. Introduction

Mathematical modelling of the human thermal system goes back to 70 years ago. Most of the works have been carried out in the framework of occupational medicine or indoor climate conditions design. Numerous procedures have been published as ISO- or ASHRAE standards. In the past four decades more detailed, multi-node models of human thermoregulation have been developed, e.g. Stolwijk (1980), Konz et al. (1977), Wissler (1985), Fiala et al. (2001), Havenith (2001), Huizenga et al. (2001) and Tanabe et al. (2002). Parsons (2014) gives a comprehensive overview. These models simulate phenomena of the human heat transfer inside the body and at its surface taking into account the anatomical, thermal and physiological properties of the human body. Heat losses from parts of the body to the environment are modelled in detail considering the inhomogeneous distribution of temperature and thermoregulatory responses over the body surface. Analysis of the human thermal environment is the subject of special investigation among scientists serving at different disciplines such as climatologists, urban planners, architects, biologists, and physicians. The assessment of biometeorological conditions for tourism and recreational purposes is usually based on fundamental meteorological data, climate-tourism indices or biometeorological indices (McGregor, 2012). Thermal comfort can be defined clearly through different approaches. A psychological perspective defines thermal comfort as a condition of mind that expresses satisfaction with the thermal environment. It is an outcome of energy balance between the human body surface and the environment, and it is influenced by human physiology, psychology and behavior (Jendritzky et al., 2012; McGregor, 2012).

One of the fundamental issues in human biometeorology is the assessment and forecast of the outdoor thermal environment in a sound, effective and practical way This is due to the need for human beings to balance their heat budget in any climate to a state very close to thermal neutrality in order to optimize their comfort, performance and health (Jendritzky et al., 2008). Human thermal comfort models, on the other hand, consider in addition to atmospheric parameters (air temperature, water vapor pressure, wind speed and mean radiant temperature (Kántor & Unger, 2011)) complex metabolic processes including physical activity level and clothing insulation. Human thermal comfort indices such as Physiologically Equivalent Temperature (PET) (Höppe, 1999; Matzarakis et al., 1999; Mayer & Höppe, 1987) is based on the Munich Energy-Balance Model for Individuals (MEMI) and the Klima–Michel model with Perceived Temperature (PT) as the equivalent temperature (Jendritzky et al., 2000; Staiger et al., 2012) have been commonly used in human-biometeorological assessments during the last decade (Burkart et al., 2011; Gabriel & Endlicher, 2011; Jendritzky et al., 2009; Kim et al., 2011; Laschewski & Jendritzky, 2002; Matzarakis et al., 2011).

In order to determine thermal stress, several factors, including air temperature, wind velocity, water vapor pressure, short- and long-wave radiant fluxes, physiological strain, behavior and the autonomous human thermoregulatory system, need to be considered (Havenith, 2001; Jendritzky et al., 2009; Parsons, 2014).There are more than 100 indices used to assess thermal health hazards. The first group of indices to be widely used were based on a simple two-parameter combination of air temperature and humidity for ‘warm’ indices and air temperature and wind speed (wind chill) for ‘cold’ indices (Blazejczyk et al., 2012). The UTCI equivalent temperature for a given combination of wind, radiation, humidity and air temperature is then defined as the air temperature of the reference environment that produces the same strain index value (Bröde et al., 2012). The UTCI development was performed by a multidisciplinary expert team in the framework of a commission of the International Society of Biometeorology (ISB) and of COST Action 730 (Jendritzky et al., 2009) under the ‘umbrella’ of the World Meteorological Organization Commission for Climatology (WMO-CCl).

The UTCI can be applied to key applications in human biometeorology, such as daily forecasting and warnings, urban and regional planning, environmental epidemiology and climate impact research; it is applicable for all climates.

The Universal Thermal Climate Index (UTCI) aims to assess outdoor thermal conditions in the major fields of human biometeorology in terms of a one-dimensional quantity summarizing the interaction of environmental temperature, wind speed, and humidity, and of the long wave and short-wave radiant heat fluxes. This assessment should be based on the physiological response of the human body, which in turn is simulated by a thermo physiological model. For this purpose, based on an advanced multi-node model of human thermoregulation (Fiala et al., 1999; 2001; 2010; Lomas et al., 2003). the 'UTCI-Fiala' model of thermo-physiological comfort was derived (Fiala et al., 2012)and coupled with a state-of-the-art clothing model. The UTCI was designed to be applicable in all climate regions, and global NWP ensembles can be used to forecast the UTCI anywhere in the world (Pappenberger et al., 2014)**.** The main objective of this study is to present an application of UTCI in climate valorization for the purposes of urban tourism and recreation and Zoning maps of UTCI In order to estimate the thermal comfort in Khorasan Razavi province. Another subject of interest of this study arises out of the fact that weather perception and thermal comfort are influenced, not only by microclimatic conditions (the combined impact of air temperature and humidity, wind and solar fluxes), but also by personal parameters like physical activity, clothing, age or psychological factors (motivation, individual preferences or cultural background). The secondary objective of this study is to determine whether biometeorological indices (i.e. UTCI) may accurately reflect the actual thermal state, thermal sensations and weather preferences of people engaged in tourism and recreational activities.

2. Study area

The Khorasan Razavi is a province in northeastern Iran. This province is located between the latitudes 30°-24°N and 38°-17°N and longitudes 55°-17'E and 61°-15'E. (Fig. 1). It borders North Khorasan province and Turkmenistan in the north, Semnan province in the west, Yazd and South Khorasan provinces in the south and Afghanistan and Turkmenistan in the east. Khorasan Razavi covers an area of 144,681 km² and has a population of 5,593,079 (2005). Sixty percent of population lives in 20 cities, and the remaining are residents of rural areas. This wide region with the population of over 6 million plays a crucial role in agricultural and economic sectors. It has 19 counties and Mashhad is the center and capital of the province. Other major cities are Ghoochan, Torbate Heydarieh, Torbate Jam, Kashmar, Neyshaboor and Sabzevar. The highest point of the province is Binalood at 3615m and the low-lying area in the Sarakhs plain is approximately 299 m above sea level. Factors such as the area of the province, high mountains, being close to the desert areas in the west and south West, stay away from the sea and the different winds, has caused a variety of climates in various areas of the province.

3. Materials and Methods

In this study meteorological data including, temperature (˚C), wind speed (m/s), cloudiness (okta)[1] and relative humidity (%) were obtained from 10 synoptic station on a daily time scale during 2004-2013 period. Mean radiation temperature (Tmrt) was calculated by Ray Man software and finally using Bioklima software daily values of UTCI were calculated for each station. UTCI equivalent temperature categorized in terms of thermal stress for each month in stations. Then by using Pearson correlation model, the relationship between UTCI and elevation was studied ($p\text{-value}<0.05$) and the Simple Linear Regression Models were provided for each month. Finally according to regression equations and based on Digital Elevation Model (DEM) UTCI monthly zoning maps were obtained using ArcGIS 10.2.1 software.

3.1. Universal thermal climate index

In 1999, the International Society of Biometeorology (ISB) established a Commission 'On the development of a Universal Thermal Climate Index *UTCI*'. The goal of this project was to derive a thermal index based on the most advanced thermophysiological model.

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[1] okta is a unit of measurement used to describe the amount of cloud cover at any given location such as a weather station

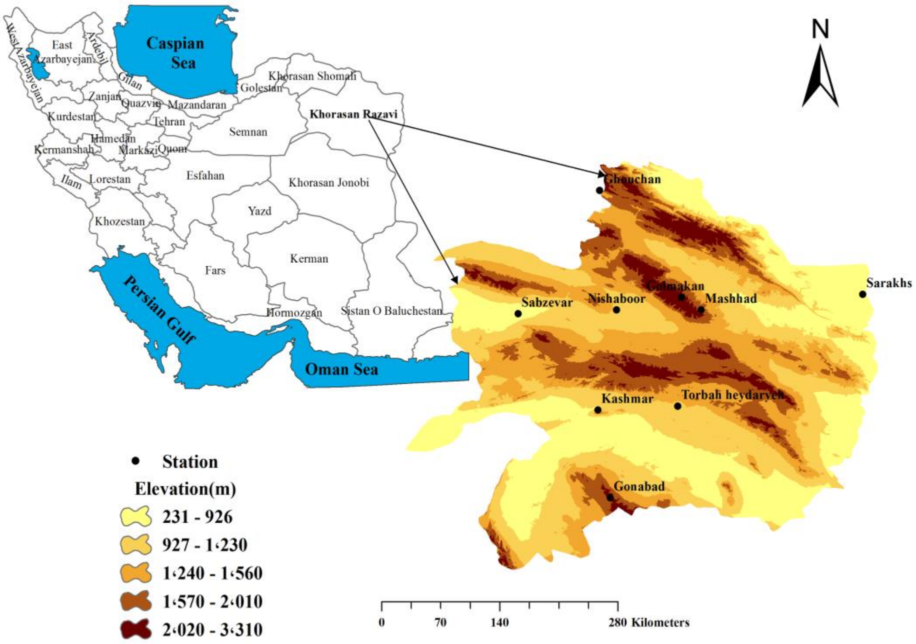

Fig. 1. The geographical location of Khorasan Razavi Province, Iran

Since 2005, these efforts have been reinforced by European COST (Cooperation in Science and Technical Development) Action 730, which has brought together leading experts in the areas of human thermo physiology, physiological modelling, meteorology and climatology, with a view to the Universal Thermal Climate Index, *UTCI*, being developed The *UTCI* is defined as the air temperature (*Ta*) of the reference condition causing the same model response as actual conditions (Blazejczyk et al., 2013).

$$UTCI = f\left(Ta;Tmrt;Va;vp\right) = Ta + offset\left(Ta;Tmrt;Va;vp\right) \tag{1}$$

The offset, i.e. the deviation of *UTCI* from air temperature, depends on the actual values of air and mean radiant temperature (*Tmrt*), wind speed (*va*) and humidity, expressed as water vapor pressure (*vp*) or relative humidity (*RH*). This indicator aims to quantify the human physiological reactions to the one-dimensional thermal conditions, as Figure 2 shows reflect actual index value will be calculated as a multivariable dynamic model (Fiala et al., 2012; Havenith et al., 2012). Finally this indicator aims to quantify one-dimensional human physiological responses to reflect the actual thermal conditions. As Figure 1 shows the index will be calculated as a multivariate dynamic model (Bröde et al., 2012; Kampmann et al., 2008).

3.2. Body construction and assessment scale of the UTCI

The UTCI-Faial model consists of 12 spherical or cylindrical body compartments: head, face, neck, shoulders, thorax, abdomen, upper and lower arms, hands, upper and lower legs, and feet (Fig. 2). Body elements are built of annular concentric tissue layers (section A-A in Fig. 1): brain, lung, bones, muscles, viscera, fat, and skin (Fiala et al., 1999) and are subdivided into a total of 63 spatial sectors. Skin is modelled as two layers (Lemons, 1984; Weinbaum et al., 1984): cutaneous plexus, i.e. blood-perfused inner layer; and outer skin which contains sweat glands but no thermally significant blood vessels. This superficial skin layer also simulates the vapor barrier for moisture diffusion through the skin in the model. The model represents an average person with a body surface area of 1.85 m^2, body weight of 73.4 kg, and body fat content of 14%. The overall physiological data of the computer humanoid replicates a reclining adult with a basal whole body metabolism of 87.1 W, basal evaporation rate from the skin of 18 W, cardiac output of 4.9 L min^{-1}, skin blood flow of 0.4 L min^{-1}; and skin wettedness of 6% (Fiala et al., 2012). The characterization of the model response should be indicative for the physiological and thermoregulatory processes as listed in Table 1, which are significant for the human reaction to neutral, moderate and extreme thermal conditions (Kampmann et al., 2008; Kuklane et al., 2007; Psikuta et al., 2012).

Outputs from the model-dependent physiological processes, including the regulation of temperature is shown in Table 1. These outputs of the human response to natural thermal conditions, moderate or severe, are important.

3.3. The assessment scale of the UTCI

The different values of the *UTCI* are categorized in terms of thermal stress. The present approach looks at responses to reference conditions and deducts the load (i.e. the heat or cold stress) caused by the organism's physiological response to actual environmental conditions (Blazejczyk et al., 2013).

This index can also be calculated on the basis of mathematical relations :(Błażejczyk, 2011)

$$UTCI = 3.21 + 0.872.T + 0.2459.Tmrt + (-2.5078.V) - 0.0176.RH \qquad (2)$$

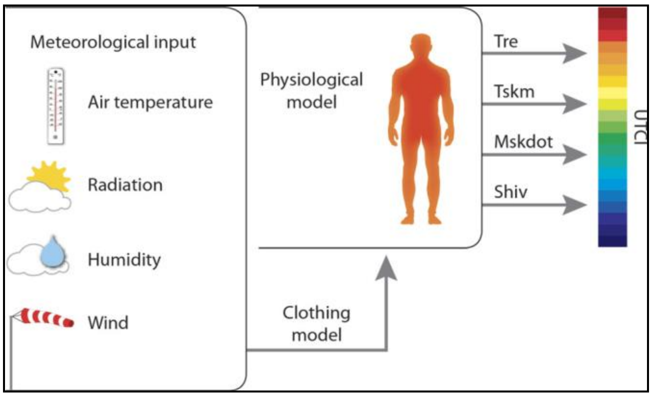

Fig. 2. Input and output data of UTCI

Table 1. Variables available from the output of the thermo-physiological model after exposure times of 30 and 120 min

Variable	Abbreviation	Unit
Rectal temperature	Tre	°C
Mean skin temperature	Tskm	°C
Face skin temperature	Tskfc	km
Sweat production	Mskdot	g/min
Heat generated by shivering	Shiv	W
Skin wettedness	wettA	% of body area
Skin blood flow	VblSk	% of basal value

Table 2. Temperature thresholds (°C) of particular thermal sensations (of alert descriptions) used in bioclimatic indices

UTCI range (°C)	Stress category
Above +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress[a]
+9 to 0	Slight cold stress
0 to −13	Moderate cold stress
−13 to −27	Strong cold stress
−27 to −40	Very strong cold stress
Below −40	Extreme cold stress

[a] The UTCI subinterval +18 to +26°C within this category complies with the definition of the "thermal comfort zone" (The Commission for Thermal Physiology of the International Union of Physiological Sciences, 2003)

where:

$\mathrm{T}: AirTemperature\,^{\circ}C$

$Mrt : Mean\ Radiant\,Temperature\,^{\circ}C$

$V\ : Wind\ velocitya\ at\ 10m\ above\ ground\ \left(m.s^{-1}\right)$

$RH\ : \mathrm{Re}lative\ humidity\ of\ \ air\,(\%)$

One input datum involved in the calculation of the *UTCI* is mean radiant temperature, a value that characterizes the thermal impact of solar radiation and air temperature on human beings. It represents a uniform surface temperature of an imaginary enclosure surrounding the person.

Mrt was calculated in line with the equation:(Błażejczyk, 2004)

$$Tmrt = \left[\left(R' + 0.5.Lg + 0.5.La\right) \Big/ \left(S_h.S\right) \right]^{0.25} + \left(-273\right) \tag{3}$$

where:

$R' : Solar\ radition\ absorbed\ by\ a\ nude\ man\left(W.m^{-2}\right)$

$Lg\ : Ground\ \ radiation\left(W.m^{-2}\right)$

$S_h\ : The\ emissivity\ cofficient\ for\ the\ human\ body\ \left(=0.95\right)$

$S\ : The\ Stefan\ Boltzmann\ cons\ \mathrm{tan}t\left(=5.667.10^{-8}, W.m^{-2}.K^{-4}\right)$

(Blażejczyk, 2011).

4. Results and Discussion

4.1. Evaluation indices UTCI

UTCI is an equivalent temperature defined for a walking person (4 km/h) with adaptive clothing (Havenith et al., 2012). in referent outdoor conditions with 50% relative humidity, still air, and Tmrt equaling air temperature (Jendritzky et al., 2012). Wind speed at 10-m height is used for the UTCI calculation (by definition) (Bröde et al., 2012)., in comparison with other indices, UTCI is more sensitive to even slight changes in temperature, solar radiation, humidity and wind speed and better describes various climatic conditions, which might be an opportunity for more appropriate human-biometeorological assessments (Blazejczyk et al., 2012; Weihs et al., 2012). Thus, UTCI allows all kinds of human thermal stress and discomfort to be addressed, e.g., cold (warm) and extreme cold (warm) ambient temperatures, increased air velocities, dry and humid environments, and conditions in which the human heat balance and the perception of the outdoor thermal environment are affected by solar radiation (Schreier et al., 2013). In the present study the calculated values of UTCI were classified according to Stress category (Table 2) for all stations. UTCI equivalent temperature categorized in terms of thermal stress for each month in stations were shown in Table 3. Based on the information in this table a class of cold stress (slight, moderate or strong) is dominant in all stations on Jan, Feb, Nov and Dec and only in the Sarakhs station Strong Heat Stress (SHS) category was observed for 3 months (Jun, Jul, Ague).

According to the correlation coefficients between the UTCI and elevation stations (Table 4) these relations for 7 months (Apr, May, Jun, July, Aug, Sep and Oct) are negative and significant (p-value<0.05). The highest correlation coefficient has been in June (r=-0.68) and the lowest correlation was observed in January (r=-0.23). Simple linear regression equations between UTCI and elevation are presented (Table 4) in which Y is the UTCI index and X is the elevation stations.

Zoning maps of UTCI for seven months (April to October) are shown in Figure 4, the highest values of UTCI were observed in the lowlands of the province in the months of May and June. Sarakhs station in East Province had the highest amount of UTCI so in terms of thermal stress, strong heat stress is dominant and there is the possibility of injury, such as in July. Also, there is the highest heat stress in the East, South and South east of the province during these months (June, Jul and Aug). In the North and central areas of the province, severe cold stress were observed compared to the other parts of the province.

Table 3. UTCI equivalent temperature categorized in terms of thermal stress for each month of each station

Station	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Ghoochan	MCS	MCS	SCS	NTS	NTS	NTS	NTS	NTS	NTS	NTS	SCS	MCS
Mashhad	MCS	MCS	SCS	SCS	NTS	NTS	NTS	NTS	NTS	SCS	SCS	MCS
Sabzevar	MCS	MCS	MCS	SCS	NTS	NTS	NTS	NTS	NTS	SCS	MCS	MCS
Golmakan	MCS	MCS	SCS	NTS	NTS	NTS	NTS	NTS	NTS	NTS	SCS	MCS
Gonabad	MCS	MCS	SCS	SCS	NTS	NTS	NTS	NTS	NTS	NTS	SCS	MCS
Neyshaboor	MCS	MCS	SCS	SCS	NTS	NTS	NTS	NTS	NTS	SCS	MCS	MCS
Torbat-Jam	MCS	MCS	MCS	SCS	NTS	NTS	NTS	NTS	NTS	SCS	MCS	MCS
Torbat-Heydareyeh	MCS	MCS	SCS	SCS	MHS	NTS	NTS	NTS	NTS	SCS	SCS	MCS
Kashmar	SCS	SCS	NTS	NTS	MHS	MHS	MHS	SHS	MHS	NTS	NTS	SCS
Sarakhs	SCS	SCS	NTS	NTS	NTS	SHS	SHS	SHS	MHS	NTS	NTS	SCS

MCS: Moderate Cold Stress, SCS: Slight Cold Stress, NTS: No Thermal Stress, MHS: Moderate Heat Stress, SHS: Strong Heat Stress

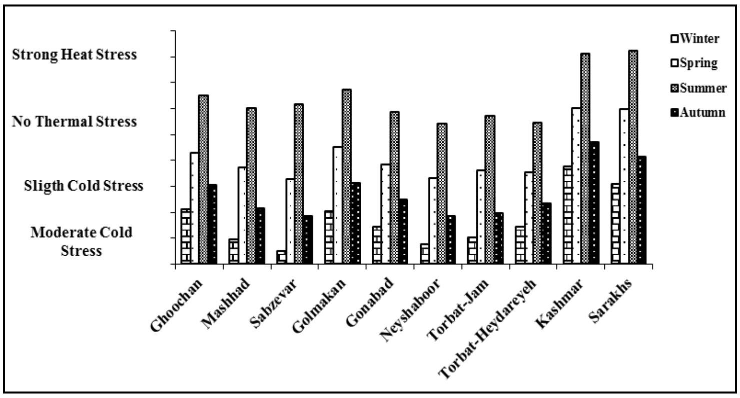

Fig. 3. Thermal sensation votes versus UTCI values

Table 4. Simple linear regression between (elevation and UTCI value) April to October

Month	Regression model	P-Value*	R
April	$Y = -0.0086x + 19.791$	0.1	-0.54
May	$Y = -0.009x + 27.95$	0.04	-0.638
June	$Y = -0.0099x + 33.883$	0.02	-0.684
July	$Y = -0.0098x + 35.788$	0.03	-0.678
August	$Y = -0.0096x + 33.30$	0.04	-0.613
September	$Y = -0.0087x + 26.609$	0.1	-0.49
October	$Y = -0.007x + 18.514$	0.2	-0.40

*The significance level=0.05

4.2. Zoning of UTCI

The height difference creates a different climate and the comfortable condition. Based on the regression equation and a digital elevation model, zoning maps UTCI index for seven months (April to October), which had a strong negative relationship with height, was prepared (Fig. 4). Most of the northern and central highlands provinces (2020m-3310m) in April and October are less cold stress Also, in areas with low altitude (926m-231m) in the months of June, July and August were observed that in July both the intensity and extent were increased so that there is a risk of heart attacks, muscle cramps due to the heat, Syncoub (faint heat) and hypothermia body.In May, and September, most parts of the province in terms of heat stress are very low except for a very small range of 3310-2020 m elevations that slight cold stress conditions prevail. In general, East, South and South East regions of province in June, July and August have the highest levels of thermal stress and in the zones of the north and center of the province, especially in April and October cold stress is dominated significantly more than other parts of the province. In May and September thermal stresses are low, so many parts of the province are without any thermal stress that this is considered in terms of bioclimatology and tourism.

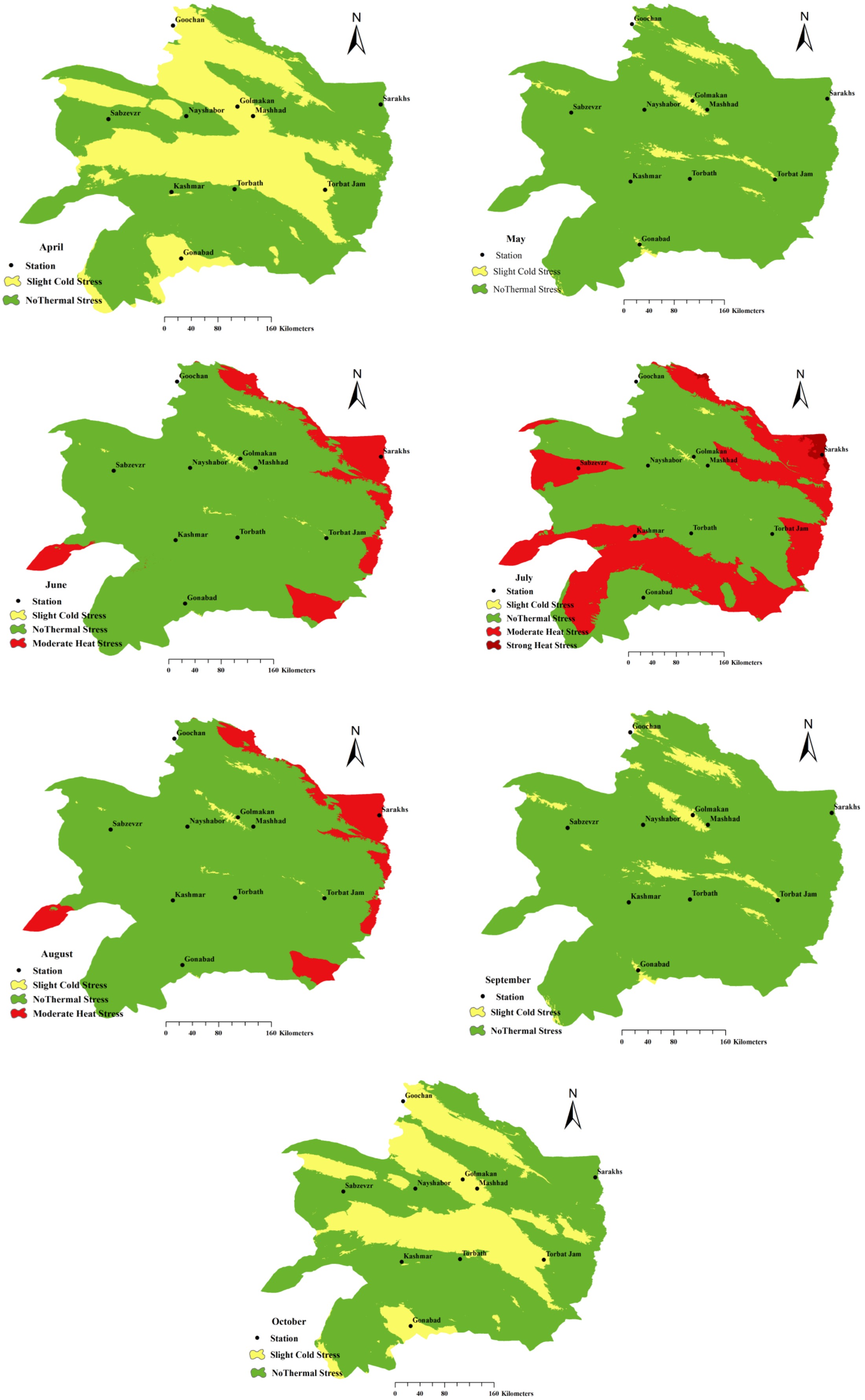

Fig. 4. Zoning heat stress conditions during April-October

5. Conclusions

The Fiala model has been subject to general as well as application-specific validation studies regarding human thermal and regulatory behaviors (Fiala et al., 2001), occupant comfort in buildings (Lomas et al., 2003), transient indoor climate conditions in cars (Fiala et al., 2004), asymmetric radiation scenarios and exposures to high intensity sources (Richards & Fiala, 2004), but also anesthesia and clinical trials studies show that there is a close relationship between temperature and respiratory and cardiac mortality (Anderson & Bell, 2009).

Previous and similar studies show that thermal stresses have the highest relationship to humidity and radiation in warm environments, as well as to wind speed in cold climates also the influence of various types of land use, thus in shaping bio-thermal conditions it is strong.(Broede et al., 2013; Milewski, 2013). Results of the study by Abdel-Ghany and his colleagues (2013) also showed that both the PET and UTCI scales can be used successfully for the arid environment to evaluate the thermal sensation, and heat stress and their results are almost similar.

In this study emphasis was on the UTCI sensitivity and effectiveness of the height of each area. Highlands in northern and central parts of the province (representative station: Sabzevar, Neyshaboor and Ghoochan) in April and October to experience a slight cold stress and the eastern and southern parts of the province due to the low altitude in the months of June, July and August heat stress condition is prevailed. In the May and September throughout the province except the peaks of the mountains are without thermal stress and in comfort. Similar studies have been conducted in this regard. The only difference is that they do not consider elevation (Bleta et al., 2014; Farajzadeh et al., 2015). The development of UTCI requires co-operation of experts from thermo-physiology, thermo-physiological modelling, occupational medicine, meteorology data handling and in particular radiation modelling, application development etc. In order to achieve significant progress, it is necessary that the relevant scientists join together on a regular basis. It is thus evident that for such a multidisciplinary task a COST Action provides the best framework to derive a health related climate index as a standard.

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