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Review Article

The Universal Thermal Climate Index UTCI Compared to Ergonomics Standards for Assessing the Thermal Environment

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Abstract: The growing need for valid assessment procedures of the outdoor thermal environment in the fields of public weather services, public health systems, urban planning, tourism & recreation and climate impact research raised the idea to develop the Universal Thermal Climate Index UTCI based on the most recent scientific progress both in thermo-physiology and in heat exchange theory. Following extensive validation of accessible models of human thermoregulation, the advanced multi-node 'Fiala' model was selected to form the basis of UTCI. This model was coupled with an adaptive clothing model which considers clothing habits by the general urban population and behavioral changes in clothing insulation related to actual environmental temperature. UTCI was developed conceptually as an equivalent temperature. Thus, for any combination of air temperature, wind, radiation, and humidity, UTCI is defined as the air temperature in the reference condition which would elicit the same dynamic response of the physiological model. This review analyses the sensitivity of UTCI to humidity and radiation in the heat and to wind in the cold and compares the results with observational studies and internationally standardized assessment procedures. The capabilities, restrictions and potential future extensions of UTCI are discussed.

Keywords: Thermal Stress, Index, Model, Ergonomics, Standards

Introduction

The projected climate change[1)] will probably influence the occupational exposure to thermal stress and thus affect health, productivity and well-being of the workforce, especially when working outdoors, e.g. in agriculture or building and construction industry in regions with already stressful thermal environments like low and middle-income tropical countries[2–4)].

Climate change impact research could make use of international standards existing for the separate assessment of cold[5)] and heat stress[6, 7)], with potential applicability to e.g. the regional evaluation of heat stress[8)]. However, assessing the influence of climate change on a global scale[6,

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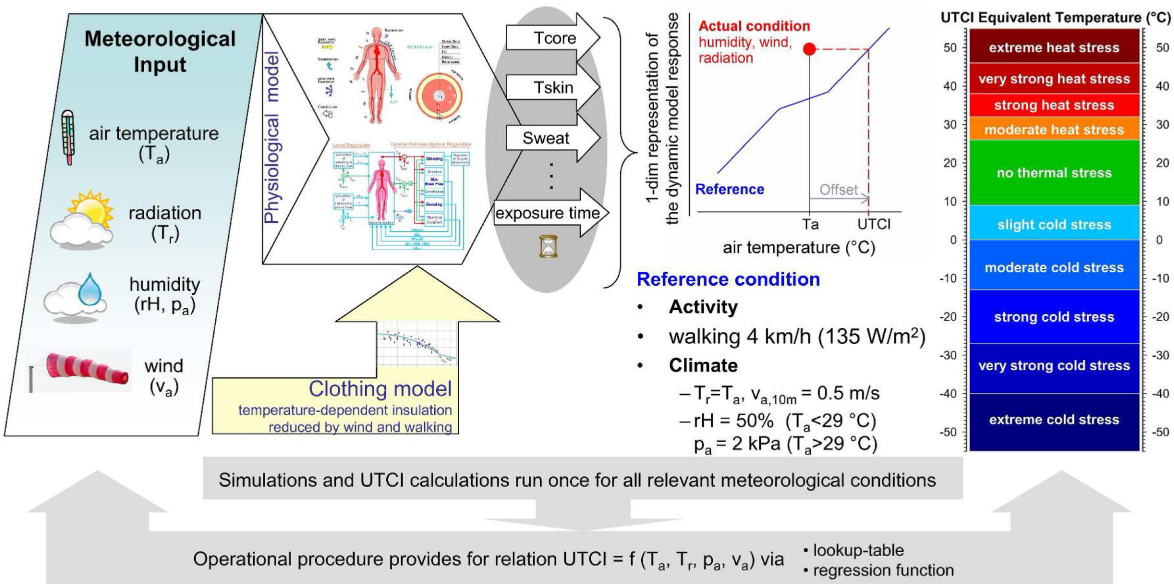

Fig. 1. Elements of the operational procedure and concept of UTCI as categorized equivalent temperature derived from the dynamic response of a thermo-physiological model coupled with a behavioral clothing model.

[9] requires approaches that are universally applicable for different seasons and climatic conditions from extreme cold to extreme heat.

These considerations and the growing need for valid assessment procedures of the outdoor thermal environment in the fields of public weather services, public health systems, urban planning, tourism & recreation and climate impact research raised the idea to develop the Universal Thermal Climate Index UTCI based on the most recent scientific progress in human thermo-physiology, in biophysics and heat exchange theory. This was recently accomplished by a group of over 40 scientists from 23 countries collaborating within COST (a European Union program promoting Cooperation in Science and Technology) Action 730[10]. Below, we briefly review the concept of UTCI and its operational procedure, as illustrated by Fig. 1.

Concept and elements of UTCI

Following extensive validation of accessible models of human thermoregulation[11], the advanced multi-node 'Fiala' model was adopted for this project[12]. This model was coupled with a state-of-the-art clothing model[13] considering (i) the behavioral adaptation of clothing insulation by the general urban population to actual environmental temperature, (ii) the distribution of the clothing over different body parts providing local insulation values for the different model segments and (iii) the reduction of thermal and evaporative clothing resistances caused by wind and the movement of the wearer, who was assumed walking at 4 km/h on the level corresponding to a metabolic rate of 135 W/m^2.

UTCI was developed conceptually as an equivalent temperature allowing for the interpretation of the index values on a familiar scale with unit °C. This involved the definition of a reference environment with 50% relative humidity (but vapor pressure not exceeding 2 kPa), with calm air and radiant temperature equaling air temperature, to which all other climatic conditions are compared. Thus, for any combination of air temperature, wind speed, radiation, and humidity, UTCI is defined as the air temperature in the reference condition which would elicit the same physiological reaction as predicted by the dynamic response of the physiological model, cf. Fig. 1. Based on criteria derived from the simulated physiological responses, the UTCI values were further categorized into ten categories of thermal stress ranging from 'extreme cold stress' to 'extreme heat stress'[14].

As running the physiological UTCI-Fiala model in routine application would require a certain level of expert knowledge and to facilitate a widespread use of UTCI, the operational procedure was completed by simplified algorithms for computing UTCI values from air temperature (Ta), wind speed (va), mean radiant temperature (Tr) and water vapor pressure (pa) as input by a table-lookup approach or by regression equations. Both simplified methods were based on data matrices generated by physiological simulations over a grid of relevant meteorological conditions defined by combinations of Ta, Tr, va and pa (Fig. 1). They are available online as supplementary information to the published operational procedure[14] or from the project's website (http://www.utci.org).

Objectives

Thermal indices are useful instruments to summarize the interaction of thermal stressors, like humidity at elevated air temperatures[15], or wind speed in cold conditions[16]. In order to test the applicability of UTCI under cold and heat stress, the purpose of this review is to analyze the sensitivity of UTCI to humidity and radiation in the heat and to wind in the cold. The results are compared with experimental data and standardized assessment procedures. The capabilities, restrictions and potential future extensions of UTCI are discussed.

Methods

The sensitivity of UTCI to heat radiation was compared with the 'Predicted Heat Strain' index (PHS, ISO 7933) in terms of the maximum allowable exposure criteria[7, 17], i.e. the time for rectal temperature to exceed 38°C or for sweat loss to exceed 7.5% of body mass. For UTCI the offsets (=UTCI-Ta, cf. Fig. 1), and for PHS the maximum allowable exposure time (DLim PHS) were computed for Ta from 20°C to 60°C and Tr-Ta from 0°C to 60°C. The further settings were chosen according to the UTCI reference condition, with intrinsic clothing insulation (Icl) decreasing according to the UTCI-clothing model[13] from Icl=0.72 clo at Ta=20°C to Icl=0.20 clo at Ta=60°C, with 135 W/m^2 metabolic rate, with 50% relative humidity, but vapor pressure below 2 kPa, and with relative air velocity var=1.14 m/s, corresponding to walking 4 km/h with omnidirectionally measured va=0.3 m/s. UTCI values were computed applying the algorithms of the operational procedure[14], PHS calculations were performed using the program published in the standard ISO 7933[17, 18].

The effects of humidity in the heat were illustrated by psychrometric diagrams showing equivalence lines for UTCI compared to contours of DLim PHS and of the Wet Bulb Globe Temperature (WBGT, ISO 7243)[6, 19], respectively. Further, the predictions of steady-state values of rectal temperature and sweat rate by PHS and the UTCI-Fiala model[12] were compared to published data[20]. These data were obtained in more than 40 laboratory experiments where three acclimatized male participants each walked for 3 h with 4 km/h on a treadmill at the level wearing clothing insulation of Icl=0.7 clo, with radiant temperature equal to air temperature and air velocity va=0.3 m/s. For each participant there were 12 to 15 exposures with different air temperatures and humidities. The averaged rectal temperatures (Tre) and sweat rates during the third hour of exposure were used to calculate a best-fit area according to a heuristic approach. By this the intra-individual variation is averaged as to facilitate a comparison with the predictions for the corresponding climatic conditions of the PHS and of the UTCI-Fiala model in psychrometric diagrams, for details cf.[21, 22]. Predictions of Tre and sweat rates by PHS and by the UTCI-Fiala model were calculated with clothing insulation, activity level, air velocity and radiation corresponding to the experimental conditions. Prediction bias and root-mean-squared errors (rmse) of UTCI and PHS were calculated for 5 equidistant combinations of air temperature and water vapor pressure along each equivalence line estimated from the experimental data (cf. Fig. 5). For comparison to WBGT, the reference value calculated according to ISO 7243, Annex C for a clothing insulation Icl=0.6 clo, for the specified workload and acclimatized persons was WBGT=28°C corresponding to an assumed maximum value of Tre=38.0°C, cf. ISO 7243, Annex A[6, 19].

In the cold, the mutual effect of air temperature and wind speed was assessed by calculating contours of UTCI and comparing them to Indices from ISO 11079[23]: Wind-Chill Temperature[16], minimum Required Insulation (IREQmin) and duration limited exposure (IREQDLim)[24] calculated using a JAVA applet[25] for air temperatures between 0 and −50°C and for wind speeds (10 m above the ground) between 0.5 and 30 m/s. Activity level, humidity and radiation were set according to the UTCI reference condition. The clothing insulation increased from Icl=1.49 clo at Ta=0°C to Icl=4.55 clo at Ta=−50°C according to the UTCI-clothing model[13] with air permeability set to 1 l/m^2/s.

Results

Heat radiation in warm environments

The offsets of UTCI to Ta (=UTCI-Ta) are shown in Fig. 2 as a function of the magnitude of heat radiation expressed as Tr-Ta for different air temperatures with wind and humidity according to the UTCI reference condition. These offsets increased linearly with radiation intensity by about 3 K per 10 K increment in mean radiant temperature, as indicated by the regression function.

For comparison to the responses of UTCI, Fig. 3a shows that radiant heat shifted the temperature-response-curve for DLim PHS to the left, indicating that with radiation the maximum allowable exposure time is reached at lower air temperatures. This shift was quantified by calculating the half-effective Ta, i.e. the Ta causing half of the maximum effect (=4 h) on DLim PHS as indicated by the circles and broken vertical lines. Regression analysis (Fig. 3b) demonstrated for PHS that − for a given Ta − a 10 K increment in Tr causes a 3.8 K decrease in the half-effective Ta. Thus the magnitude of the heat radiation effect on DLim PHS was similar to that on UTCI shown in Fig. 2.

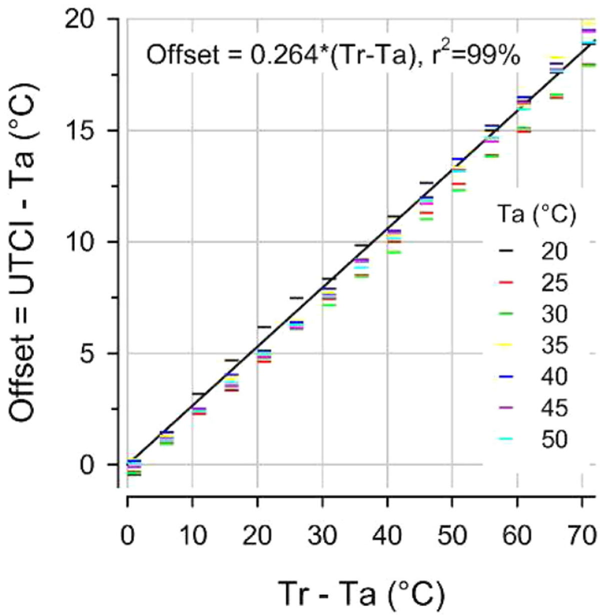

Fig. 2. The Offset (=UTCI-Ta) related to the intensity of heat radiation (Tr-Ta) for different values of Ta.

The linear regression line with equation and proportion of variance explained (r^2) are inserted. Wind speed and humidity were set according to the UTCI reference condition.

Humidity in warm environments

Fig. 4 illustrates the mutual influence of humidity and air temperature in warm climates using equivalence lines within a psychrometric diagram. For UTCI contours with limit values of different stress categories (cf. Fig. 1) indicating the transition from 'no thermal stress' to 'moderate heat stress' (26°C) and further to 'strong heat stress' (32°C), 'very strong heat stress' (38°C) and 'extreme heat stress' (46°C) are depicted. The resulting equivalence lines were curved to the left indicating an increase of UTCI with increasing humidity. As shown by the more curved lines, this increase grows larger for higher temperatures and higher humidity levels. The shape for the maximum allowable exposure criterion calculated by PHS was in good agreement with the UTCI contours, whereas WBGT indicated a stronger influence of humidity at lower values of vapor pressure.

The PHS contour indicating the limitation of maximum allowable exposure time below 8 h runs within the UTCI category 'very strong heat stress' (38°C<UTCI<46°C). This PHS contour was calculated for non-acclimatized persons and may thus be compared to the line for WBGT=26°C, which is the critical or reference value for non-acclimatized persons under these conditions[6]. Figure 4 shows that the limiting lines for WBGT and PHS coincide for very dry conditions only and that with increasing humidity the WBGT limits are conservative, i.e. they run

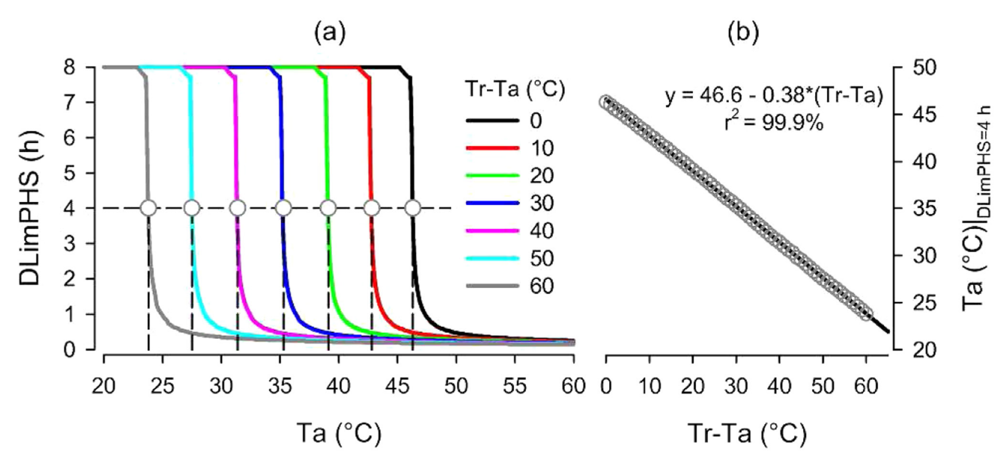

Fig. 3. Maximum allowable exposure times (DLim PHS) calculated by PHS related to air temperature for different radiation intensities (a) with circles and dashed lines denoting the half-effective Ta (i.e. Ta with half-maximum DLim PHS = 4 h), whose dependency on radiation intensity expressed by Tr-Ta is depicted in (b).

along lower air temperatures compared to PHS and across the UTCI categories ‘strong heat stress’ and ‘moderate heat stress’.

For the rectal temperature data shown in Fig. 5 the shape of equivalence lines for the predictions from the UTCI-Fiala model was in good agreement with the psychrometric charts obtained from human exposures, and the prediction bias was almost zero with rmse of about 0.1°C (Table 1). Although PHS yielded comparable prediction errors (Table 1), the contours showed qualitative discrepancies for less severe conditions with predicted Tre below the critical value of 38°C (Fig. 5, right panel). Only the contours for higher values of Tre lines were bent leftwards in a similar way as for the experimental data. The left panel of Fig. 5 also includes the reference value of WBGT = 28°C corresponding to an assumed maximum rectal temperature of 38°C for these conditions[6]. Compared to the contour lines from the experimental data this indicates a positive bias, i.e. an overestimated physiological strain by 0.4–0.5°C for WBGT. Our results are in line with earlier reports on the more preventive assessment of thermal strain by WBGT compared to PHS[26, 27] or UTCI[22]. As shown by Table 1, PHS and UTCI also provided for reasonable predictions of sweat rate, as it had also been demonstrated for UTCI with other strain characteristics like heart rate and skin temperature[11, 22].

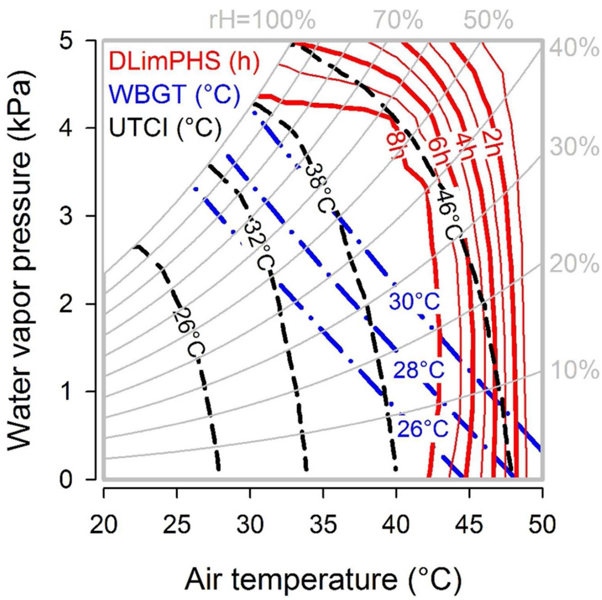

Fig. 4. Contours related to air temperature and vapor pressure (rH=relative humidity) in the psychrometric diagram of UTCI (dashed lines), of WBGT (dash-dotted lines) and of maximum allowable exposure times (DLim PHS, solid lines), calculated by PHS for a non-acclimatized person as time for Tre to exceed 38°C or for sweat loss to exceed 7.5% of body weight. Clothing insulation, activity level, wind speed and radiation were set according to the UTCI reference condition.

Table 1. Mean prediction error (bias) and root-mean-squared error (rmse) for rectal temperatures and sweat rates predicted by PHS and UTCI for experiments with humans on the effect of temperature and humidity with clothing insulation Icl=0.7 clo.

	PHS		UTCI	
	bias	rmse	bias	rmse
Rectal temperature (°C)	–0.05	0.14	0.04	0.11
Sweat rate (g/h)	66	123	3	205

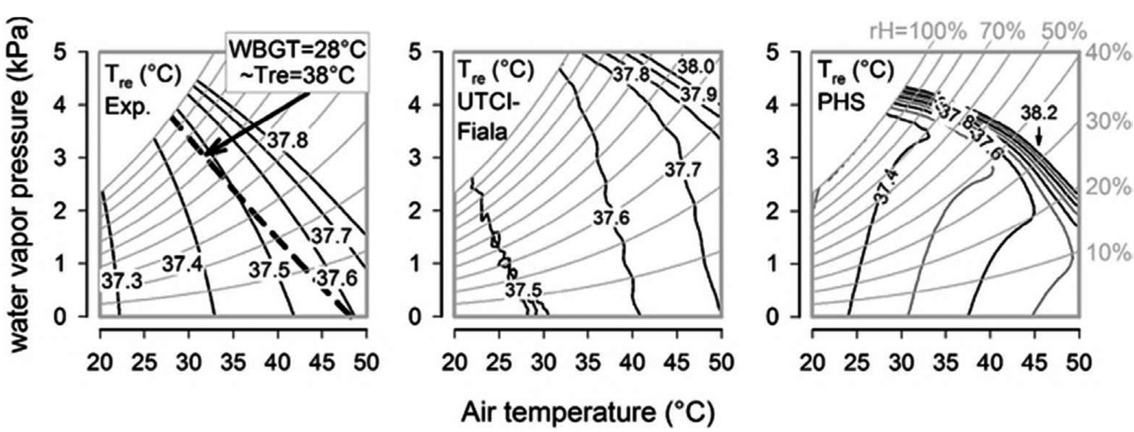

Fig. 5. Contour lines of equal rectal temperatures (Tre) after 3 h treadmill work (4 km/h) with Icl = 0.7 clo related to air temperature and vapor pressure (rH=relative humidity) from the experimental data (Exp, left panel) and from simulations by the UTCI-Fiala model (mid panel) and PHS (right panel), respectively. A dashed line for WBGT = 28°C (reference value for the work load corresponding to Tre = 38.0°C) is inserted into the left panel for experimental data.

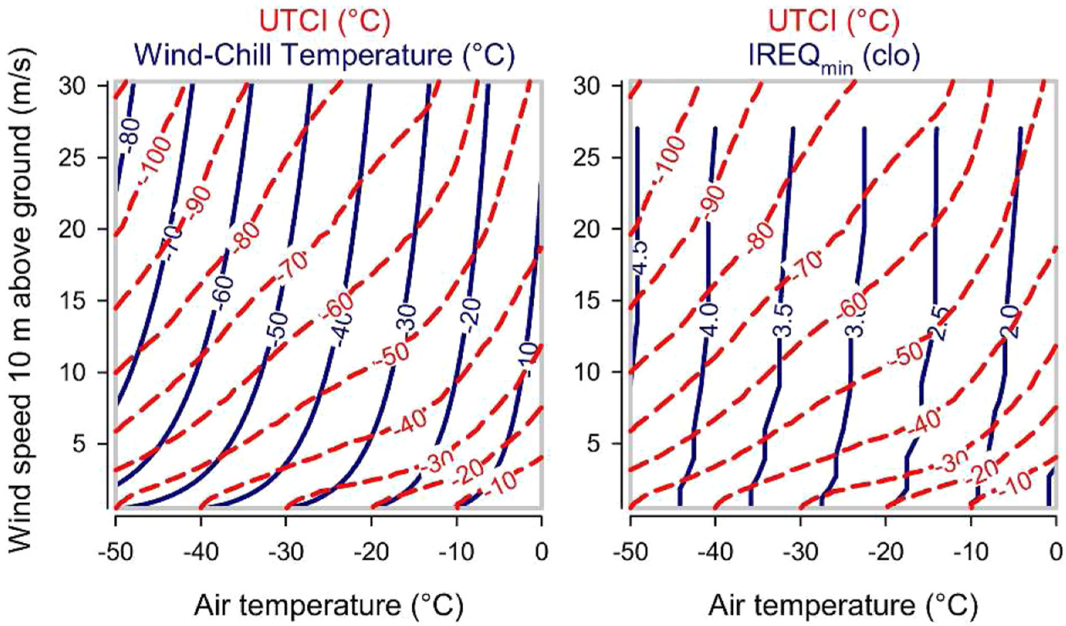

Fig. 6. Contours of UTCI (dashed lines) compared to indices from ISO 11079 (2007), Wind-Chill Temperature (left panel) and minimum Required Insulation (IREQmin, right panel) for air temperatures between 0 and −50°C and for wind speeds between 0.5 and 30 m/s. Humidity and radiation were set according to the UTCI reference condition.

Wind speed in cold environments

In the cold, decreasing temperature and increasing wind speed lowered the values of UTCI, wind-chill temperature and duration limited exposure by IREQ (IREQ DLim), but increased minimum required insulation (IREQmin). Consequently, the equivalence lines shown in Figs. 6 & 7 were all curved to the right with a flatter curvature indicating a higher sensitivity to wind speed.

Thus, UTCI indicated a more pronounced influence of wind speed above 3 m/s compared with the wind chill temperature[16)], as shown in the left panel of Fig. 6. This is probably related to different assumptions made by both approaches: Whereas the wind chill temperature focuses on facial cooling under steady state conditions with an assumed core temperature of 38°C, UTCI considers the dynamic response of the whole body.

The index "Required Clothing Insulation" IREQ[23)], which also focuses on the whole body response to cold stress, requires far higher values of Icl at a given temperature than the value of the UTCI clothing model calls for[13)], even for minimum requirements IREQmin. This may partly explain the quite low influence of wind speed also below 3 m/s in IREQmin compared to UTCI (Fig. 6, right panel).

For comparing the sensitivity to wind of those indices, it might be more sensible to calculate duration limited exposure values also for the IREQ standard, as those values are derived from the physiological reaction, i.e. cooling of the body. Equivalence lines of IREQ DLim (Fig. 7), which were calculated for a person clothed according to the UTCI model[13)], showed an excellent agreement with equivalence lines of UTCI. This demonstrates that for a given clothing insulation the predictions of heat loss by IREQ are in accordance with the dynamic physiological response of the UTCI model.

Discussion and Outlook

The results of this study indicate that UTCI may become a useful tool to assess the combined influence of ambient temperature, wind, humidity and radiant heat fluxes on outdoor working conditions, while being based on the most recent scientific progress in both thermo-physiology and heat exchange theory, and being easily applicable if the required input parameters are at hand. Special attention should be given to the mean radiant temperature, which often is difficult to obtain in bio-meteorological application scenarios and which has considerable influence on the acuity of the UTCI calculation[28, 29)], as it was similarly discussed for the impact of globe temperature on the acuity of WBGT[8)].

When assessing the discrepancies observed in the

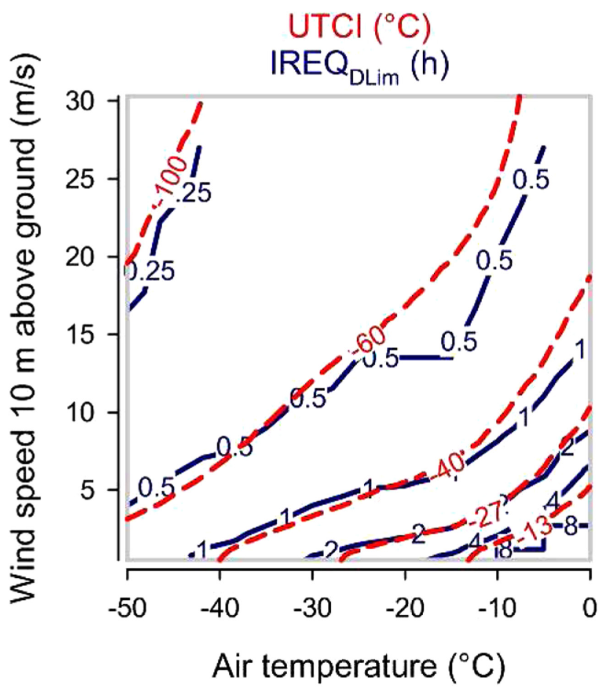

Fig. 7. Contours of UTCI (dashed lines) compared to duration limited exposure (IREQDLim) from ISO 11079 (2007). For environmental conditions cf. Fig. 6. Clothing insulation decreased with air temperature according to the UTCI-clothing model.

comparisons with other ergonomics standards, one should consider differences in the tools' objectives and underlying assumptions. WBGT aims at providing a simple method for heat stress assessment at industrial workplaces and its reference values "have been established allowing for a maximum rectal temperature of 38°C for the persons concerned"[6]. PHS, in contrast, limits the average rectal temperature to 38°C in order to keep the probability for reaching 39.2°C and 42°C below 10^{-3} and 10^{-6}, respectively[7]. In addition, PHS assumes an average rehydration rate of 60%[26], so that the maximum allowable exposure criteria of 7.5% of body mass loss complies to a net dehydration of 3% of body mass, which is considered as maximum allowable in industrial settings[7]. Thus it is not unexpected that WBGT was shown here and in earlier studies[22, 26, 27] to be more sensitive to heat stress than PHS or UTCI. Furthermore, this property of WBGT may be considered desirable as it corresponds to the strategy of applying a simple screening tool like WBGT for a fast first heat stress assessment with the option to apply a more detailed rational analysis like PHS (or UTCI) if the WBGT reference value is exceeded[6].

Nevertheless, the results of the comparison studies and the plausible dependency of UTCI on humidity and radiation in warm environments as well as to wind speed in cold climates suggest that UTCI has the potential to provide a valid and easy-to-use assessment of the physiological response to both cold and heat stress. Thus, with regard to the range of temperatures considered, UTCI may be regarded as widely applicable for assessing impacts of climate change on the thermal stress at workplaces on a global scale.

Currently, UTCI uses fixed values of metabolic rate and, connected to air temperature, of clothing insulation and only depends on the four physical determinants of the thermal environment. This limits the applicability of UTCI, as the in depth analysis of working conditions will as well require the consideration of varying workloads, exposure times and of protective clothing[30] as prescribed by the occupational situation. There are attempts to integrate those effects into standardized assessment procedures[31], but current heat stress standards still do not include all the processes related to the hampered heat and moisture transfer with highly insulating protective clothing[32, 33], the increased energy consumption due to clothing weight and bulkiness[34] or the effects of behavioral adaptation like self-pacing[35]. Nevertheless, the high level of detail devoted to the modeling of the physiological[12] and clothing system[13] as well as the extensive validation work[11, 22, 36] provide the basis and the flexibility for expanding UTCI to the comprehensive assessment of occupational thermal strain. First promising results have been shown in this paper for the experiments with Icl = 0.7 clo over a range of temperature and humidity conditions.

Conclusion

We conclude that UTCI provides a valid assessment of the human physiological response to thermal stress ranging from extreme cold to extreme heat. It is based on contemporary science in thermo-physiology and biophysical modeling which will allow resolving current limitations with respect to occupational settings imposed by the assumed activity level and clothing behavior. However, the expansion of the UTCI approach still requires considerable future research effort because of the exponentially increasing demand on simulation time by systematically varying further dimensions like metabolic rate, clothing characteristics and exposure time in addition to the physical determinants of the thermal environment.

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