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THE UNIVERSAL THERMAL CLIMATE INDEX UTCI FOR ASSESSING THE OUTDOOR THERMAL ENVIRONMENT.

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INTRODUCTION

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 (Psikuta et al., 2011), the advanced multi-node ‘Fiala’ model was adopted for this study (Fiala et al., 2011). This model was coupled with a state-of-the-art clothing model (Havenith et al., 2011) considering (i) the behavioural 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 4 km/h on the level corresponding to a metabolic rate of 135 W/m².

UTCI was developed conceptually as an equivalent temperature (Bröde et al., 2011). This involved the definition of a reference environment with 50% relative humidity (but vapour pressure not exceeding 2 kPa), with still air and radiant temperature equalling air temperature, to which all other climatic conditions are compared. 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 physiological reaction as predicted by the dynamic response of the physiological model (Figure 1; Bröde et al., 2011).

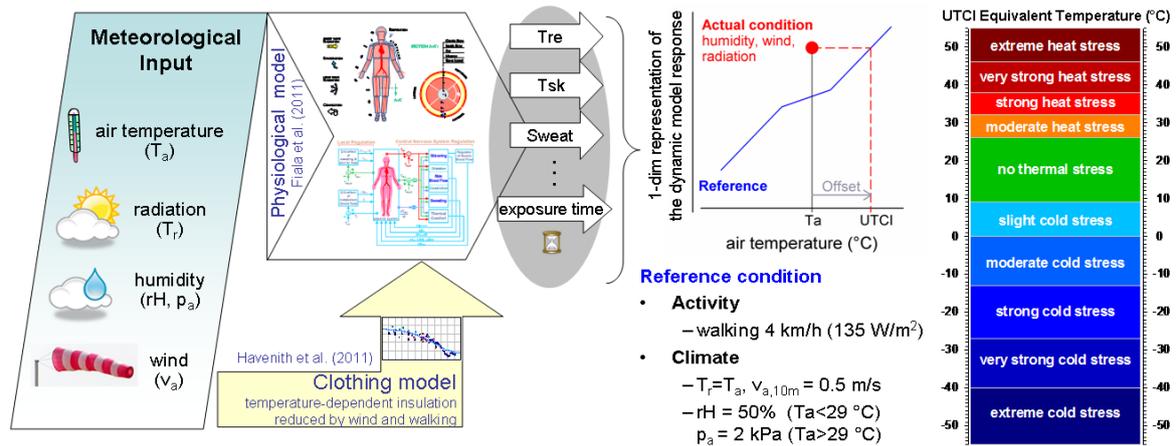


Fig. 1 Concept of calculating UTCI for an actual condition, which is defined as air temperature of the reference condition yielding the same dynamic physiological response

This paper analyses the sensitivity of UTCI to humidity and radiation in the heat and to wind in the cold compared to experimental data and to standardised assessment procedures. The capabilities, restrictions and potential future extensions of UTCI are discussed.

METHODS

The responses of UTCI were compared to the effects of **heat radiation** on one of the criteria used to calculate the duration limited exposure in the index ‘Predicted Heat Strain’ (PHS) (ISO 7933, 2004): the time for rectal temperature to exceed $38 \text{ }^\circ\text{C}$ (DLim Tre). The criterion was computed for T_a from $20 \text{ }^\circ\text{C}$ to $60 \text{ }^\circ\text{C}$ and $T_r - T_a$ from $0 \text{ }^\circ\text{C}$ to $60 \text{ }^\circ\text{C}$. The further conditions were 0.5 clo clothing insulation, 135 W/m^2 metabolic rate, humidity according to the reference condition and relative air velocity $v_a = 1.15 \text{ m/s}$ (walking 4 km/h in still air).

The effects of **humidity in the heat** were illustrated by psychrometric diagrams showing equivalence lines for UTCI compared to contours of DLim Tre from PHS and of the Wet Bulb Globe Temperature (WBGT) (ISO 7243, 1989), respectively. Further, the predictions of steady-state values of rectal temperature and sweat rate by PHS and the UTCI-Fiala model (Fiala et al., 2011) were compared to data obtained in more than 100 laboratory experiments with male participants wearing clothing insulation of $I_{cl} = 0.1, 0.7$ and 1.0 clo , respectively (for details cf. Kampmann et al., 2011b). Activity level, air velocity and radiation corresponded to the UTCI reference condition.

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 (2007), Wind-Chill Temperature, minimum Required Insulation (IREQ_{min}) and duration limited exposure (IREQDLim) for air temperatures between 0 and $-50 \text{ }^\circ\text{C}$ 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.

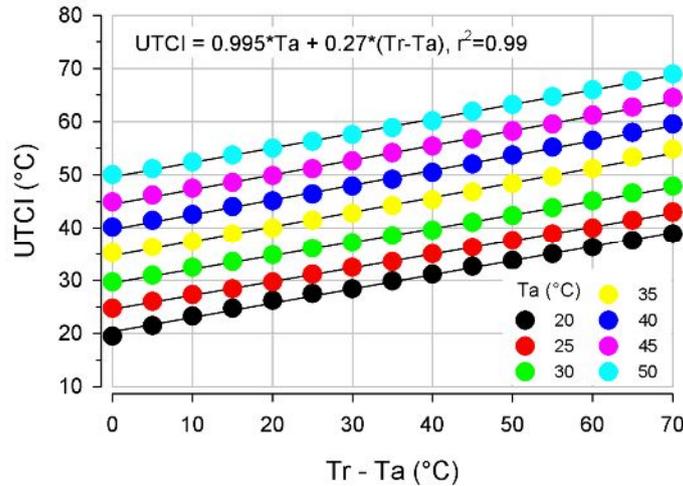


Fig. 2 UTCI related to the extent of radiation (Tr-Ta) for different values of Ta.

Wind speed and humidity were set according to the reference condition

RESULTS

Figure 2 shows UTCI as a function of the magnitude of **heat radiation** expressed as Tr-Ta for different air temperatures with wind and humidity according to the reference condition. UTCI increases linearly with radiation intensity by about 3 K per 10 K increment in mean radiant temperature, as indicated by the regression function. The regression shows, that in reference conditions with Tr=Ta UTCI almost perfectly agrees ($r^2=0.995$) with Ta, as it could be expected from the definition of UTCI.

For comparison to the responses of UTCI, Figure 3a shows that radiant heat shifted the temperature-response-curve for DLim Tre to the left, indicating that with radiation the limit 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 as indicated by the blue dots and broken lines. Regression analysis (Figure 3b) demonstrated for PHS that – for a given Ta – a 10 K increment in Tr causes a 3.7 K decrease in the half-effective Ta. Thus the heat radiation effect on PHS was similar to that on UTCI.

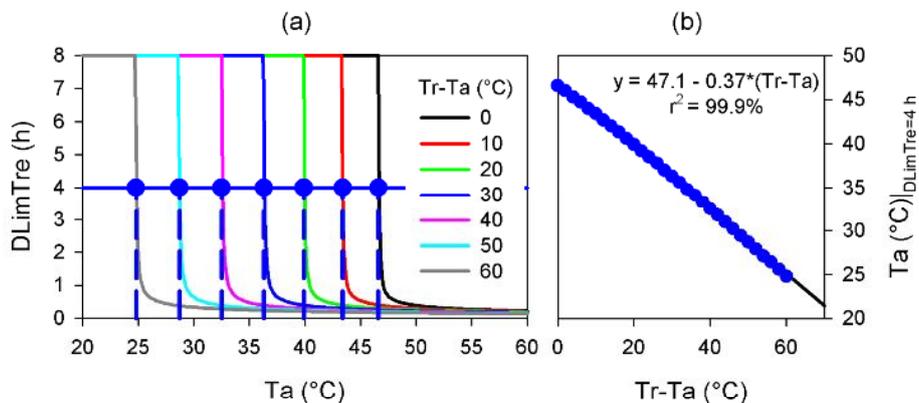


Fig. 3 Duration limited exposure values (DLim Tre) calculated by PHS related to air temperature for different radiation intensities (a) and the half-effective Ta (i.e. Ta with half-maximum effect) related to radiation intensity expressed by Tr-Ta (b)

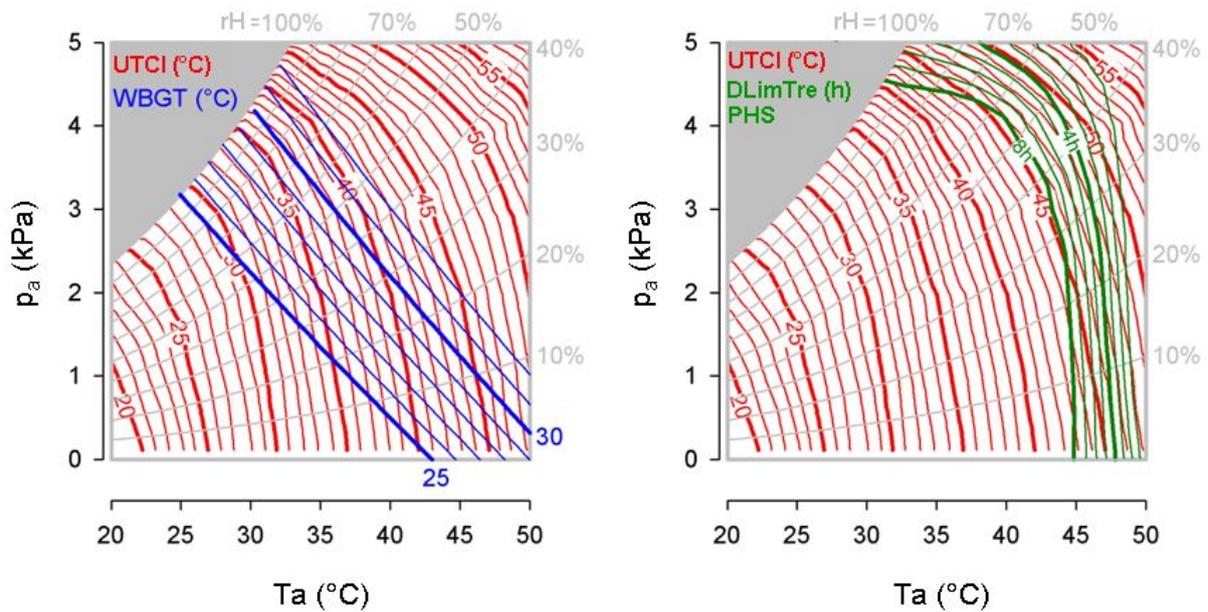


Fig. 4 UTCI related to air temperature (T_a) and vapour pressure (p_a) in the psychrometric diagram with contours of WBGT added to the left and of duration limited exposure values (DLim Tre), calculated by PHS as time for T_{re} to exceed $38\text{ }^\circ\text{C}$, added to the right panel. Activity level, wind speed and radiation were set according to the reference condition

Figure 4 shows the mutual influence of **humidity and air temperature in warm climates** using equivalence lines within a psychrometric diagram. The resulting contour lines were bent leftwards 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 duration limited exposure criterion calculated by PHS from the time for rectal temperature exceeding $38\text{ }^\circ\text{C}$ showed a good agreement with the UTCI contours, whereas WBGT indicated a stronger influence of humidity at lower values of vapour pressure. The shape of equivalence lines for UTCI within the psychrometric chart was also in good agreement with the charts obtained for physiological data from human exposures (Kampmann et al., 2011a), and the prediction errors of rectal temperature and sweat rate were of similar magnitude for PHS and UTCI (Table 1).

Table 1 Mean prediction error (bias) and root-mean-squared error (rmse) of PHS and UTCI for experiments with humans on the effect of temperature and humidity averaged over three clothing conditions with $I_{cl}=0.1, 0.7$ and 1.0 clo, cf. Kampmann et al. (2011b).

	PHS		UTCi	
	bias	rmse	bias	rmse
Rectal temperature ($^\circ\text{C}$)	-0.08	0.27	0.06	0.24
Sweat rate (g/h)	49	96	42	301

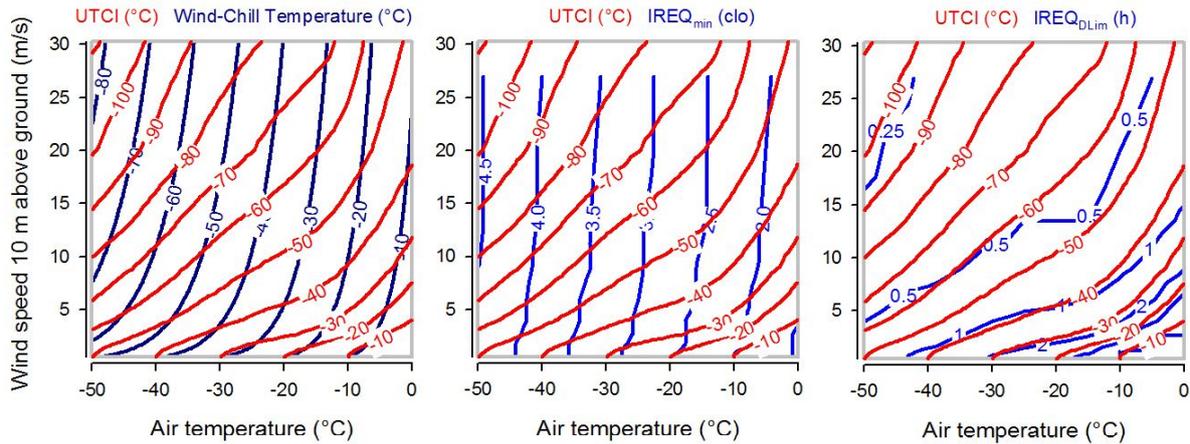


Fig. 5 Contours of UTCI compared to Indices from ISO 11079 (2007), Wind-Chill Temperature (left panel), minimum Required Insulation (IREQ_{min}, mid panel) and duration limited exposure (IREQ_{DLim}, right panel) for air temperatures between 0 and -50 °C and for wind speeds between 0.5 and 30 m/s. Humidity, radiation and; for DLim calculation; clothing were set according to the UTCI reference condition

In the **cold**, UTCI indicated a more pronounced influence of wind speed above 3 m/s compared to the wind chill temperature (Osczevski & Bluestein, 2005), as shown in Figure 5. 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 (ISO 11079, 2007), which also focuses on the whole body response to cold stress, requires far higher values of I_{cl} as the maximum value of the UTCI clothing model calls for (Havenith et al., 2011), even for minimum requirements IREQ_{min}. This may explain the quite low influence of wind speed below 3 m/s for IREQ_{min}.

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. 5, right panel), which were calculated for a person clothed according to the UTCI model (Havenith et al., 2011), show an excellent agreement with equivalence lines of UTCI. This demonstrates that for a given clothing insulation the prognoses of heat loss by IREQ are in accordance with the dynamic physiological response of the UTCI model.

CONCLUSIONS

The comparisons with other ergonomics standards and the plausible dependency of UTCI on humidity and radiation in warm environments as well as to wind speeds in cold climates suggest that UTCI has the potential to provide a valid assessment of the physiological response to both cold and heat stress. Thus, with regard to the range of temperatures considered, UTCI may be universally useable in future bio-meteorological applications.

Currently, UTCI uses fixed values of metabolic rate and, connected to air temperature, of clothing insulation. However, the high level of detail devoted to the modeling of the physiological (Fiala et al., 2011) and clothing system (Havenith et al., 2011) as well as the extensive validation work (Psikuta et al., 2011; Kampmann et al., 2011a) provide the flexibility for future extensions of UTCI, e.g. to the assessment of thermal strain at the workplace. As this would require systematic variations of metabolic rate, of clothing characteristics as well as of exposure time in addition to the physical determinants of the thermal environment, this has to be left to future research activities because of the exponentially increasing demand on simulation time.

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