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The Universal Thermal Climate Index UTCI in Operational Use

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Abstract: The Universal Thermal Climate Index UTCI provides an assessment of the outdoor thermal environment in bio-meteorological applications based on the equivalence of the dynamic physiological response predicted by a model of human thermoregulation, which was coupled with a state-of-the-art clothing model. The operational procedure, which is available as software from the UTCI website (www.utci.org), showed plausible responses to the influence of humidity and heat radiation in the heat, as well as to wind speed in the cold and was in good agreement with the assessment of ergonomics standards concerned with the thermal environment. This suggests that in this regard UTCI may be universally useable in the research and in the major areas of application of human biometeorology.

Keywords: climate index, heat stress, cold stress, simulation model, clothing

Background: Development of UTCI

For the past four years the European Union has funded within the COST Action 730 the development of the Universal Thermal Climate Index UTCI, which aims at the assessment of the outdoor thermal conditions in the major fields of human biometeorology. This assessment should be based on the physiological response of the human body, which in turn was to be simulated by a state-of-the-art thermo-physiological model.

After accessible models of human thermoregulation had been evaluated, the advanced multi-node 'Fiala' thermoregulation model was selected (Fiala et al., 1999; 2001; 2003), extensively validated (Psikuta, 2009; Psikuta et al., 2007), and extended for purposes of the project (Fiala et al., 2007). In the next step a state-of-the-art adaptive clothing model was developed and integrated (Richards & Havenith, 2007). This model considers

i. the behavioural adaptation of clothing insulation observed for the general urban population in relation to the 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.

UTCI was then developed following the concept of an equivalent temperature. 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. Equal physiological conditions are based on the equivalence of the dynamic physiological response predicted by the model for the actual and the reference environment. As this dynamic response is multidimensional (body core temperature, sweat rate, skin wettedness etc. at different exposure times), a strain index was calculated by principal component analysis as single dimensional representation of the model response (Bröde et al., 2009a; 2009b), cf. Figure 1. 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, which produces the same strain index value.

As calculating the UTCI equivalent temperatures by running the thermoregulation model repeatedly could be too time-consuming for climate simulations and numerical weather forecasts, several options to speed up this calculation were considered. These included look-up tables of pre-calculated index values for a grid of all relevant combinations of climate parameters and polynomial regression equations predicting the UTCI equivalent temperature values over the same grid (Bröde et al., 2008; 2009a).

This paper presents the application of the operational procedure, which is accessible both as software source code and executable program at the project's website (www.utci.org), on studying the sensitivity of UTCI to wind, humidity and radiation under heat and cold stress conditions compared with responses and predictions of some ergonomics standards concerned with the thermal environment. Concerning the reactions to humidity and radiation in warm environments, the Wet Bulb Globe Temperature (WBGT, ISO 7243, 1989) and the Predicted Heat Strain (PHS, ISO 7933, 2004) were used for comparison, respectively, and the response of UTCI to wind in the cold was compared to the Wind-Chill Temperature (ISO 11079, 2007; Osczevski & Bluestein, 2005).

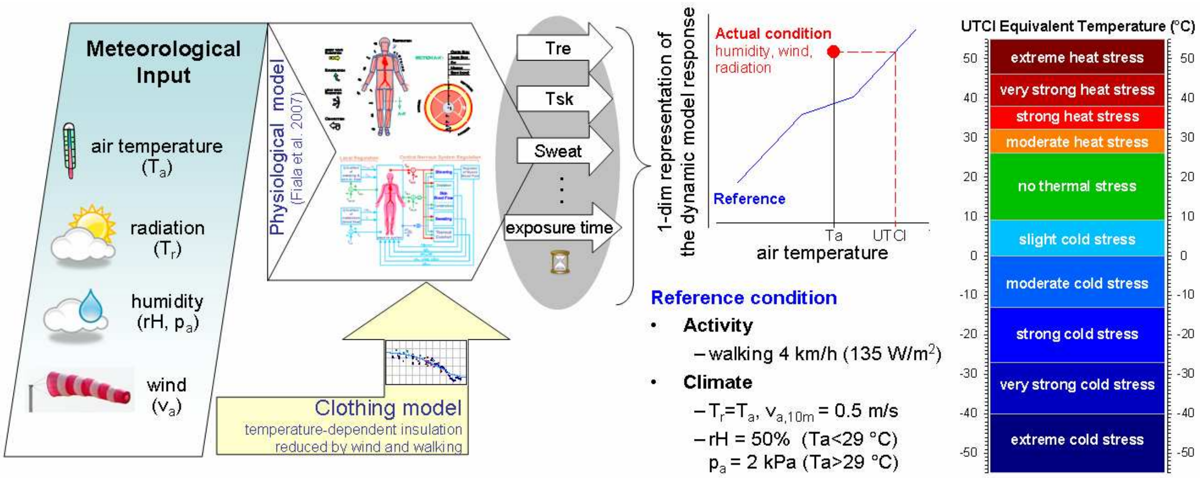

Figure 1: Concept for calculating UTCI of an actual condition, which is defined as air temperature of the reference condition yielding the same dynamic physiological response.

Responses of single variables

As different combinations of values of the single variables may lead to identical values of the single dimensional strain index, climatic conditions with the identical UTCI have, by definition, the same value of the strain index, but may yield non-unique values for single variables like rectal or mean skin temperature. However, due to the high correlation of the single variables with this strain index (Bröde et al., 2009a), this variation was limited, as indicated in Figure 2 for the rectal temperature after 2h and the dynamic thermal sensation as predicted by the physiological model (Fiala et al., 2003).

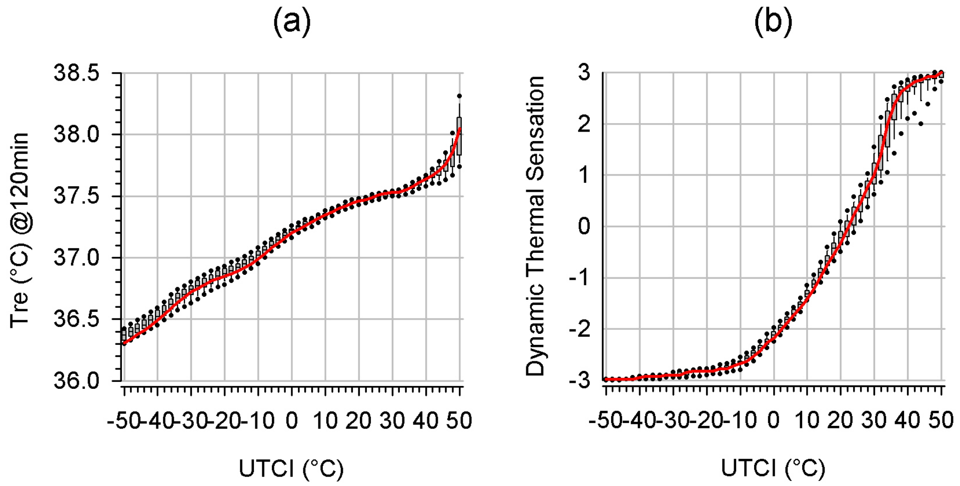

Figure 2: Box plots of rectal temperature values after 2 h (a) and dynamic thermal sensation votes averaged over 2 h (b) related to UTCI of an actual condition. The red lines denote the values for the reference conditions.

Furthermore, the median response to UTCI was in good agreement with the values obtained for the reference conditions (Figure 2). Consequently, the associated assessment scale was derived from the simulated physiological responses to the reference conditions and comprises ten thermal stress categories ranging from extreme cold stress to extreme heat stress (cf. Figure 1).

Responses of UTCI to radiation, humidity and wind

Figure 3 shows UTCI related to the intensity 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 confirms, that in reference conditions with Tr=Ta UTCI agrees almost perfectly (0.995) with Ta, as it was to be expected from the definition of UTCI.

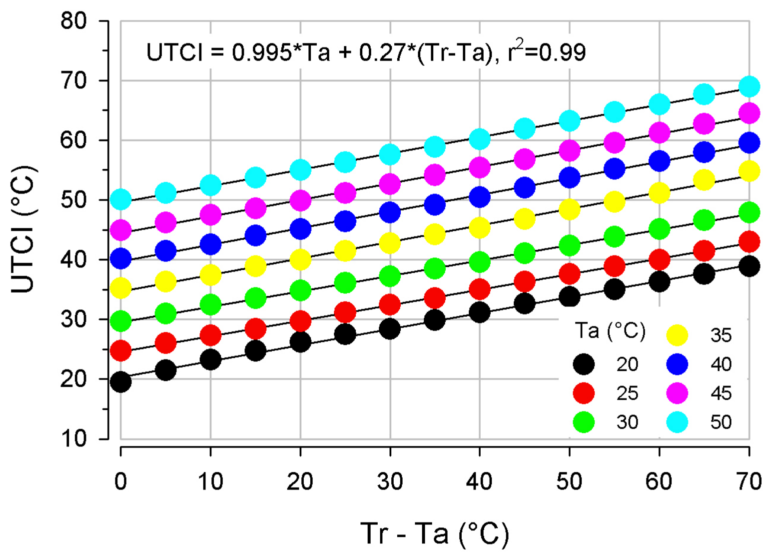

Figure 3: UTCI related to radiation intensity (Tr-Ta) for different values of Ta. Activity level, wind speed and humidity were set according to the reference condition.

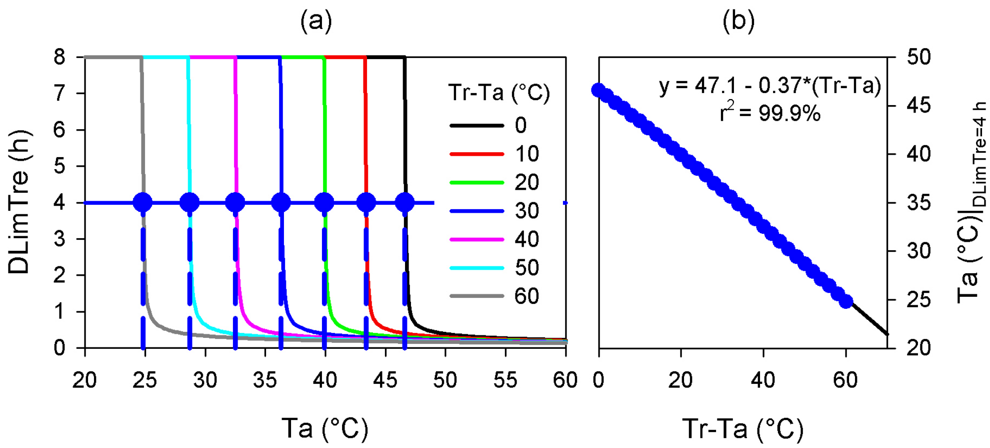

Figure 4: Duration limited exposure values (DLim Tre) calculated by PHS related to air temperature for different radiation intensities (a) and the half-effective Ta (i.e. Ta with half-maximum effect) related to radiation intensity expressed by Tr-Ta (b).

The responses of UTCI were compared to the effects of heat radiation on one criterion used to calculate the duration limited exposure in the index 'Predicted Heat Strain' (PHS): the time for rectal temperature to exceed 38 °C (DLim Tre). The criterion was computed for Ta from 20 °C to 60 °C and Tr-Ta from 0 °C to 60 °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 var=1.15 m/s, corresponding to walking with 4 km/h in still air.

Figure 4a 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 4b) demonstrated for PHS that a 10 K increment in Tr causes a 3.7 K decrease in that half-effective Ta.
For outdoor conditions with still air WBGT increases by 2 K per 10 K increment in Tr, as globe temperature equals Tr under these settings (ISO 7243, 1989). Thus the heat radiation effect on UTCI was within the magnitudes obtained for PHS and WBGT, respectively.

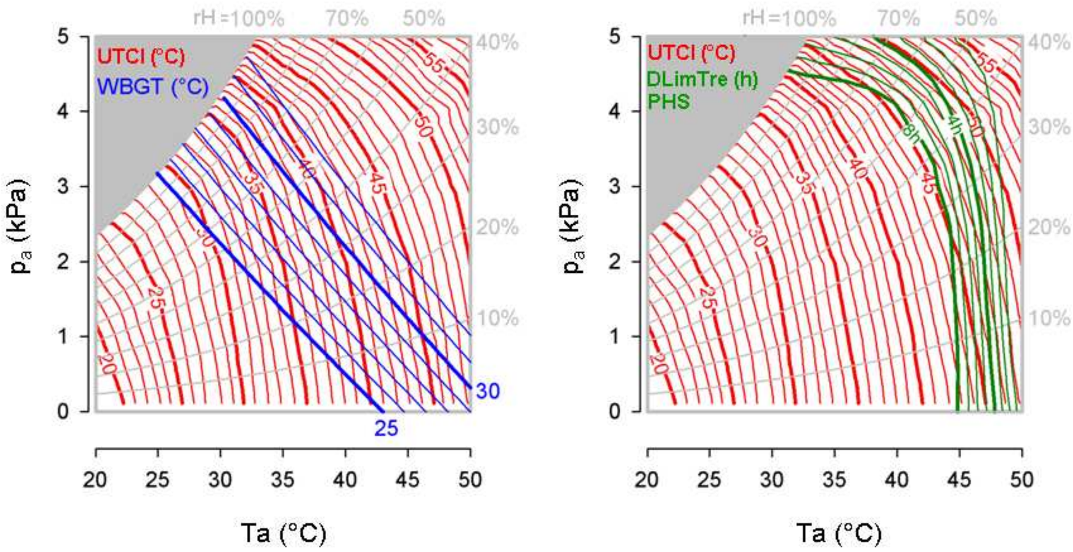

Figure 5: UTCI related to air temperature (Ta) and vapour pressure (p_a) in the psychrometric diagram with contours of WBGT added to the left and of duration limited exposure values (DLim Tre), calculated by PHS as time for Tre to exceed 38 °C, added to the right panel. Activity level, wind speed and radiation were set according to the reference condition.

Figure 5 shows the influence of humidity related to air temperature in warm climates using 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 is greater for higher temperatures and higher humidity levels. The duration limited exposure criterion calculated by PHS from the time for rectal temperature exceeding 38 °C showed a good agreement with the UTCI contours, whereas WBGT indicated a stronger influence of humidity at lower values of vapour pressure The psychrometric chart's shape for UTCI was also in good agreement with the charts obtained for physiological data from human experiments (Kampmann & Bröde, 2009).

In the cold, UTCI indicated a more pronounced effect for wind speeds above 3 m/s compared to the wind chill temperature (Osczevski & Bluestein, 2005), as shown in Figure 6. This is probably related to different assumptions underlying 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. Further comparisons should consider the index Required Clothing Insulation IREQ (ISO 11079, 2007), which also focuses on the whole body response to cold stress.

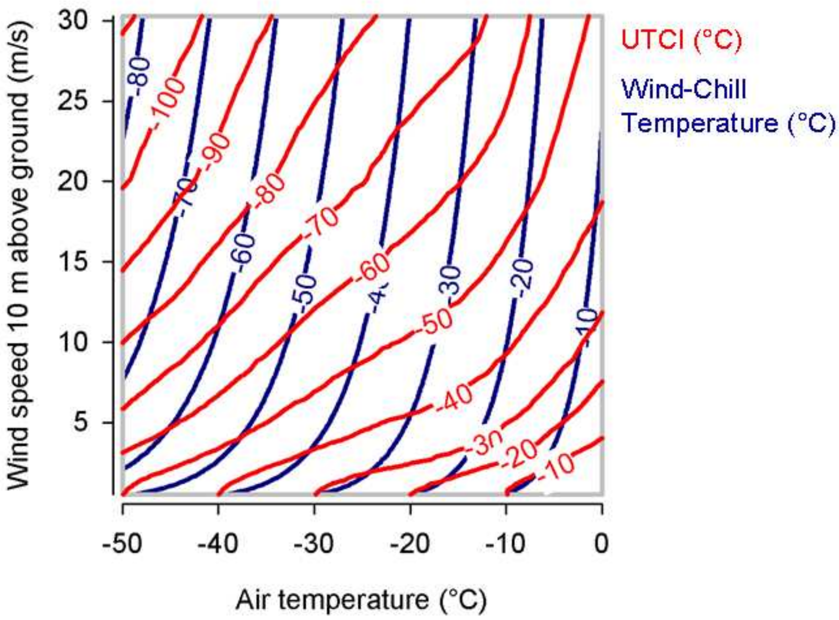

Figure 6: Contours of UTCI and Wind-Chill Temperature for air temperatures between 0 and -50 °C and for wind speeds between 0.5 and 30 m/s. Humidity and radiation were set according to the reference condition.

Conclusions

As the UTCI values calculated for the reference conditions proved to be virtually identical to air temperature, the operational procedure is consistent with the equivalent temperature approach used for developing UTCI. Furthermore, the comparisons with other ergonomics standards and the plausible reactions of UTCI to humidity and radiation in warm environments and to wind in the cold suggest that UTCI has the potential to provide a valid assessment of the physiological response to both cold and heat stress. Thus, in this regard UTCI may be universally useable in future bio-meteorological applications.

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