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Extending the Universal Thermal Climate Index UTCI towards varying activity levels and exposure times

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Abstract

The Universal Thermal Climate Index UTCI assesses the outdoor thermal environment based on the multi-node UTCI-Fiala-model of thermoregulation, which was coupled with a clothing model considering the clothing behaviour of an urban population. The applicability of UTCI to exercising, resting or occupational settings is currently limited by the assumed moderate activity level (2.3 MET) and the maximum exposure time of two hours. However, the high level of detail devoted to the modelling of the physiological and clothing system will allow for expanding UTCI to varying exposure times and activity levels, as will be demonstrated by this paper. We calculated UTCI adjustment terms for activity varying from a resting to a high (5 MET) level and for exposure duration covering an 8-hour shift length in 30-min steps. Simulations with the UTCI-Fiala model were performed using the adaptive UTCI-clothing model with air temperatures from -50°C to +50°C for UTCI reference climatic conditions. The adjustment terms indicated that thermal stress decreased with shorter exposure and increased with longer times, and that high activity increased heat stress, whereas low activity increased cold stress. Effect size was moderated by stress category with greater effects of activity and exposure time in the cold compared to moderate or warm climates. These results demonstrate UTCI's capabilities for a comprehensive assessment of dynamic thermal stress in occupational and other relevant outdoor settings. However, extensive simulations are still necessary to include the effects of special leisure and work clothes.

Keywords: thermal comfort, outdoors, model, clothing, metabolic rate

1 Introduction

The Universal Thermal Climate Index (UTCI) was developed by an international group of researchers to assess the outdoor thermal environment in the application fields of human biometeorology (Jendritzky et al., 2012). It is based on the dynamic physiological human response to cold, heat and moderate climatic conditions as simulated by the advanced multi-node UTCI-Fiala-model of thermoregulation (Fiala et al., 2012), which was coupled with an adaptive clothing model (Havenith et al., 2012) considering the clothing behaviour of an urban population. As shown by Figure 1, UTCI summarises the interaction of ambient temperature, wind, humidity and radiation fluxes as an equivalent temperature. The operational procedure (Bröde et al., 2012) was completed using an assessment scale categorising the index values in terms of thermal stress, and by simplified algorithms for calculating UTCI values without the need to run the complex simulation models.

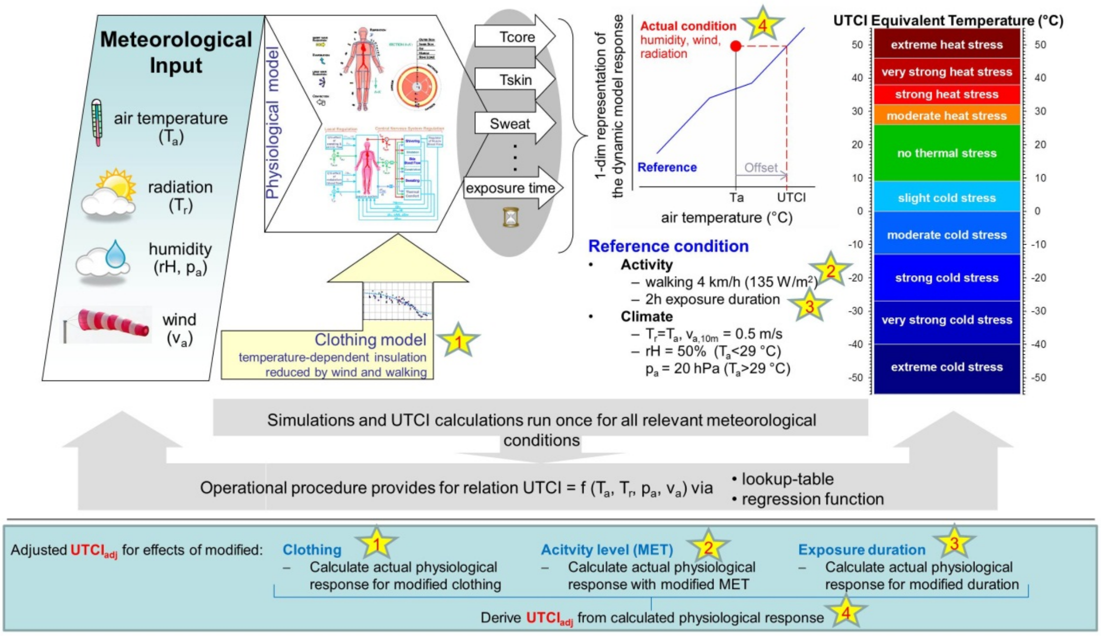

Figure 1. Concept and elements of UTCI and its operational procedure, modified from Bröde et al. (2012). The derivation of UTCI-values adjusted for non-reference clothing, activity and exposure duration ($UTCI_{adj}$) is described in the light blue box below the separating line.

The assessment of cold and heat stress by UTCI was shown to agree well with experimental data (Kampmann et al., 2012; Psikuta et al., 2012) and with international standards concerned with the ergonomics of the thermal environment (Bröde et al., 2013; Kampmann et al., 2012). But in its current stage, UTCI does not consider the characteristics of special protective clothing, and its applicability to occupational thermal stress is limited by the moderate activity level (metabolic rate of 135 W/m^2) and the maximum exposure time of two hours, which were assumed for the simulation runs.

The influence of varying clothing insulations, activity levels (metabolic rates) or exposure durations may not only impact the application of UTCI to occupational settings (Bröde et al., 2013), but also to other scenarios, like thermal comfort assessment of beach tourists (Rutty & Scott, 2015), of persons exercising in urban areas (Vanos et al., 2010), or of occupants inside buildings (Walikewitz et al., 2015).

However, the high level of detail devoted to the modelling of the physiological and clothing systems allows for expanding UTCI to a wider range of activity levels, duration and clothing, which need to be taken into account when assessing these additional settings. This paper aims at demonstrating this with respect to varying exposure times and activity levels for the UTCI reference climatic conditions, as defined in Figure 1.

2 Methods

We calculated additive adjustment terms for UTCI considering activity ranging from a resting level with metabolic rate of heat production of 1.1 MET (1 MET = 58.15 W/m2), to a very high level (ISO 8996, 2004, Table A.2) of 4.9 MET, and exposure duration covering an 8-hour shift length in 30-min steps. Simulations were performed with the UTCI-Fiala model (Fiala et al., 2012) using the adaptive UTCI-clothing model (Havenith et al., 2012).

Air temperatures varied from -50°C to +50°C in 1 K steps for UTCI reference climatic conditions as shown in Figure 1, which were defined by calm air (0.5 m/s air velocity 10 m above ground level), mean radiant temperature equalling air temperature, and 50% relative humidity (but vapour pressure not exceeding 20 hPa).

For the 9,696 combinations of air temperature, activity level and exposure time, UTCI computations were performed with the model output obtained after the actually simulated exposure times replacing the 2-hour values in the original calculations (Bröde et al., 2012). By subtracting UTCI for the reference conditions, which are equal to air temperature by definition (Bröde et al., 2012), from these calculated values, we obtained additive adjustment terms depending on UTCI, activity level and exposure time.

In order to assess the influence of clothing and walking speed (v_w), we additionally calculated adjusted UTCI values for semi-nude (0.1 clo) conditions with v_w=0 m/s simulating sitting or lying in a beach environment for 2h (Rutty & Scott, 2015), as well as for an office scenario with 8h occupancy using the “KSU-uniform” (cotton long-sleeved shirt, long trousers, underpants, socks) plus shoes with an estimated insulation of 0.6 clo (Fiala, 1998), also using v_w=0 m/s additional to the UTCI reference walking speed v_w=1.1 m/s.

3 Results and Discussion

Figures 2&3 illustrate the adjusted values of UTCI ($UTCI_{adj}$) obtained for different exposure durations and metabolic rates; Figure 4 depicts the error of using adjusted UTCI values from reference climatic conditions also for non-reference conditions; and Figure 5 shows the influence of clothing and walking speed for both an office and beach scenario, respectively.

3.1 Effects of metabolic rate and exposure duration

Figure 2 illustrates the adjusted values of UTCI ($UTCI_{adj}$) for 2h exposure with different metabolic rates. As could be expected, lower activity levels increased the limits for the UTCI stress categories, i.e. cold stress occurred at higher UTCI temperatures, as did heat stress. Contrary, with increased metabolic rate, heat stress occurred at lower UTCI values.

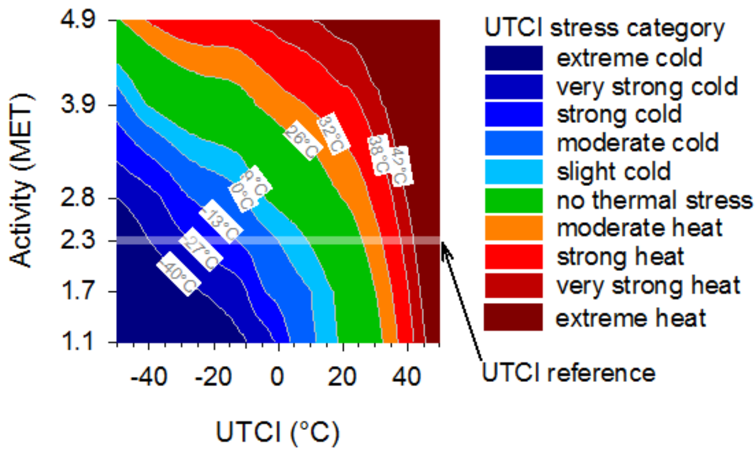

Figure 2. Contours of the $UTCI_{adj}$ adjusted to different metabolic rates (MET) for UTCI reference climatic conditions with 2h exposure duration. Labels mark the limits of the stress categories from the UTCI assessment scale (cf. Fig. 1). The arrow indicates the UTCI reference activity of 2.3 MET with UTCI=$UTCI_{adj}$.

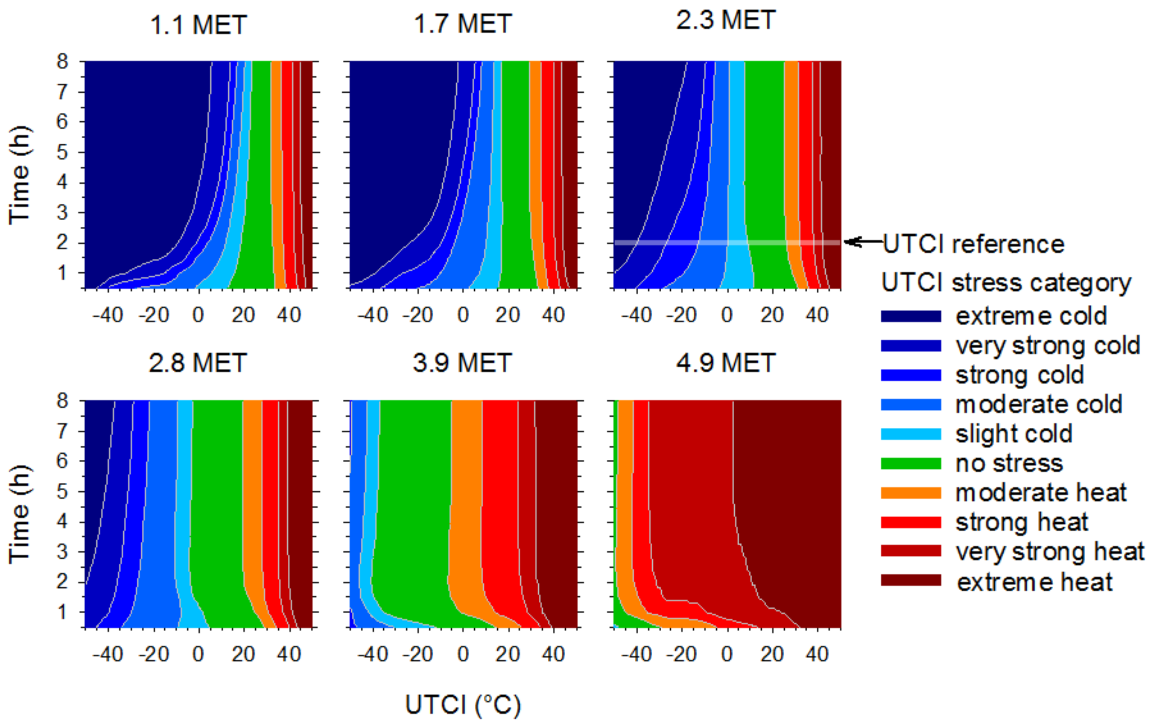

Figure 3. Contours of $UTCI_{adj}$ related to metabolic rates (MET) and exposure duration (Time) over a range of UTCI reference conditions with UTCI stress categories as in Fig. 1. The arrow indicates the UTCI reference activity and duration of 2.3 MET and 2h, respectively, with $UTCI=UTCI_{adj}$.

Looking at the additional effect of exposure duration in Figure 3 indicated that compared to UTCI reference conditions, thermal stress decreased with shorter exposure times and increased with longer times. Again (cf. Figure 2), high activity increased heat stress, whereas low activity increased cold stress. In accordance with previous research (Höppe, 2002), the magnitude of the effect was moderated by the stress category, with greater effects of activity and exposure time in the cold compared to moderate or warm climates.

Simulating high activity levels with highly-insulating clothing at low temperatures turned cold stress to heat stress conditions, as shown in Figures 2 & 3. This phenomenon agrees with field observations and laboratory studies (Rintamäki & Rissanen, 2006), but is not covered by current ergonomic standards for the assessment of cold and heat stress.

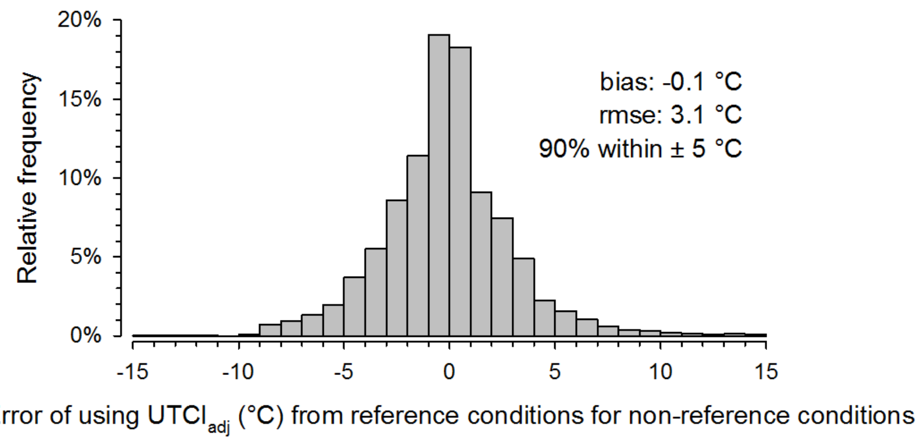

Figure 4. Error distribution of using UTCI adjustments for activity and exposure duration from UTCI reference climatic conditions to non-reference climatic conditions from ECHAM4 (Stendel & Roeckner, 1998).

3.2 Adjusted UTCI for non-reference climatic conditions

Although the UTCI reference climatic conditions considered here cover only a small portion of all relevant thermal environments (Bröde et al., 2012), the adjustment terms obtained in this study might be representative for other climates with UTCI values between -50°C and +50°C as well, because identical index values should represent equal thermal strain (Jendritzky et al., 2012). This assumption was verified for 100 randomly chosen climatic conditions from the ECHAM4 control run (Stendel & Roeckner, 1998) covering a broad range of air temperature (-36 to +40 °C), relative humidity (5 to 100%), wind speed (1 to 15 m/s), difference between mean radiant and air temperature (ΔT_{mrt} -13 to +38 °C), and UTCI values from -40 to +39 °C. Adjusted UTCI ($UTCI_{adj}$) was calculated as before for the same exposure times and metabolic rates for the UTCI reference climatic conditions. Figure 4 compares the resulting $UTCI_{adj}$ between reference and non-reference climatic conditions showing that bias was negligible. However, the root-mean squared error rmse=3.1 °C advocates for future supplemental simulation studies to investigate the effects of modified metabolic rates and exposure durations for non-reference climatic conditions.

3.3 Influence of clothing and walking speed in resting activities

Figure 5 compares the adjusted UTCI ($UTCI_{adj}$) values for scenarios with low activity (1.1 MET) experienced at office and beach, respectively, to reference UTCI (black solid lines), to UTCI adjusted for metabolic rate and exposure duration calculated for a walking person as shown in Figure 3 (open blue symbols), and to values considering the lying or sitting activity (v_w=0 m/s, filled symbols) and typical clothing of office occupants or beach tourists (red symbols for KSU-clothing and green symbols for semi-nude conditions).

For both scenarios, adjusted UTCI ($UTCI_{adj}$) was below reference UTCI, and the values for walking conditions were lower than those with zero walking speed, due to the increased convective cooling caused by the higher relative air velocity.

Given that zero walking with semi-nude clothing (filled green symbols) might represent the typical condition for beach tourists, it could be noted that the adjusted values for 1.1 MET with UTCI-clothing as shown in Figure 3 and represented in Figure 5 by open blue symbols, provided a good approximation to these 'typical' conditions for beach tourists. This might be explainable because the higher insulation of UTCI-clothing was compensated by the higher relative air velocity due to walking. It is also obvious, that 'moderate heat stress' calculated by the reference UTCI will reduce to 'no thermal stress' with $UTCI_{adj}$, similarly the higher stress categories will also be reduced to one category lower when using adjusted UTCI. This will put the findings of a corresponding survey (Rutty & Scott, 2015) reporting a preference for even 'strong heat stress' conditions as assessed by UTCI to a different perspective.

For the office scenario, UTCI-clothing and KSU-clothing gave very similar results with differences occurring only below 23 °C UTCI. If one considers the KSU-clothing with zero walking (filled red symbols) as 'typical' for office occupancy, the adjusted UTCI from Figure 3 (open blue symbols) did not provide a good approximation to those typical conditions, which was contrary to the beach scenario. For 'strong heat stress' (UTCI above 32 °C) the reference UTCI (solid black line) with 2.3 MET and walking 1.1 m/s was close to this typical condition. This happened probably because the relative air movement by walking compensated for the increased metabolic rate in this setting for heat stress conditions. For moderate heat to neutral ('no thermal stress') conditions, reference UTCI values overestimated heat stress while the values adjusted to low activity, but assuming non-zero walking speed showed underestimation, even indicating slight cold stress.

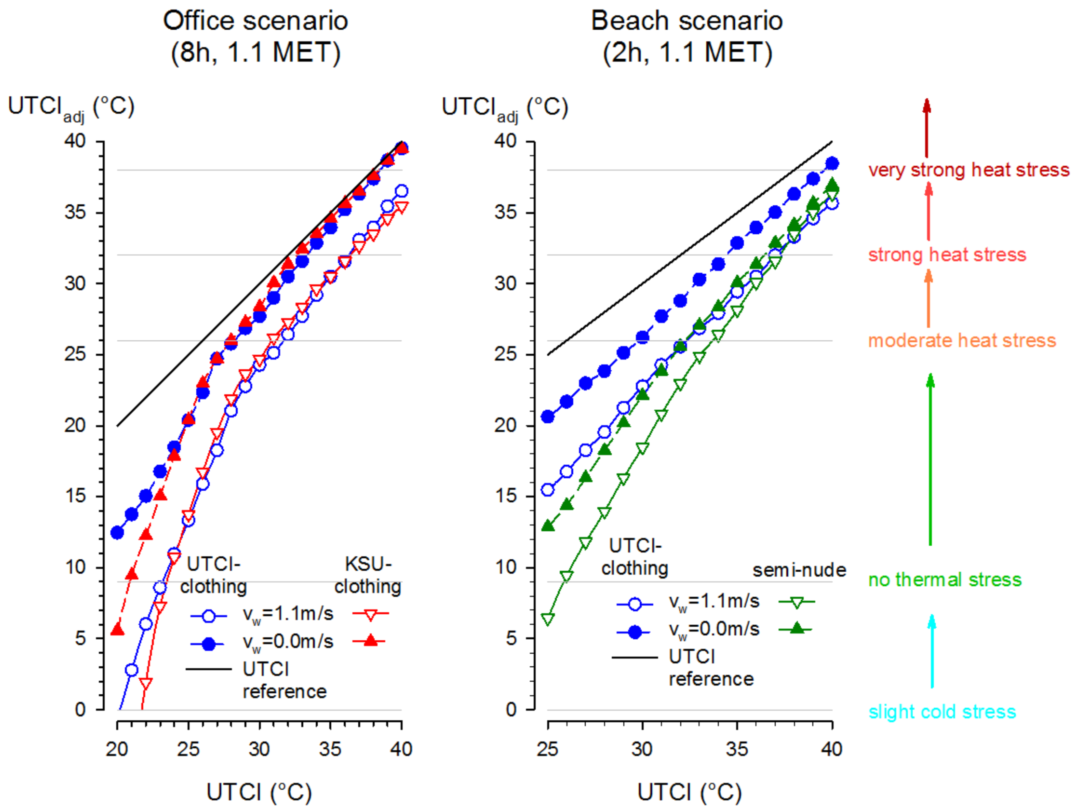

Figure 5. $UTCI_{adj}$ vs. reference UTCI for different clothing ensembles and walking speeds (v_w) simulating an office scenario with 8h occupancy and low metabolic rate (left panel), and a beach scenario (right panel), resting for 2h exposure time. The black line indicates $UTCI=UTCI_{adj}$. Horizontal reference lines correspond to UTCI stress categories (cf. Figure 1).

4 Conclusion

These results open the perspective to a comprehensive assessment of occupational thermal stress and other relevant outdoor settings using UTCI by taking into account different activity and clothing levels. As exemplified for beach tourists' thermal comfort, the use of UTCI adjusted for the lower activity level would provide a better discrimination between the roles of reduced metabolic rate and altered expectations (Rutty & Scott, 2015).

Our results also indicate a warning to be issued for the application of UTCI to indoor conditions (e.g. Walikewitz et al., 2015). Though the UTCI-Fiala-model might well be capable of simulating those conditions, as shown in Figure 5, the boundary conditions for the development of UTCI were chosen targeting outdoor environments. Thus, adjustments towards lower activity levels as presented in Figures 2 and 3 might not work well indoors.

For application purposes, the adjustment terms will be used in a two-step approach to calculate UTCI not only related to parameters of the thermal environment, but also to activity level and exposure time. First, as shown in Figure 1, UTCI values are calculated by the usual operational procedure from air temperature, humidity, wind and radiation (Bröde et al., 2012). Then, the adjustment terms depending on activity level, exposure time and UTCI are determined, e.g. by a look-up table or regression approach as for UTCI calculation, and are added to the UTCI values computed for reference activity and reference exposure time in the first step.

However, as the climatic conditions in this study comprised less than 0.1% of the relevant combinations of temperature, wind, humidity and radiation (Bröde et al., 2012), and because the effects of varying clothes were not yet systematically analysed, further extensive simulation studies are still needed.

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