1   UTCI - Why another thermal index?
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19   **Abstract**

20   The existing assessment procedures of the thermal environment in the fields of public weather
21   services, public health systems, precautionary planning, urban design, tourism & recreation
22   and climate impact research show significant shortcomings. This is most evident for simple
23   (mostly two-parameter) indices, when comparing them to complete heat budget models
24   developed since the 1960s. ISB Commission 6 took up the idea to develop a Universal
25   Thermal Climate Index (UTCI) which was to be based on the most advanced multi-node
26   model of thermoregulation representing the progress in science within the last 3 to 4 decades,
27   both in thermo-physiological and heat exchange theory.
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29   Creating the essential research synergies for the development of UTCI required pooling the
30   multidisciplinary experts in the fields of   thermal physiology, mathematical modelling,
31   occupational medicine, meteorological data handling (in particular radiation modelling) and
32   application development in a network. It was possible to extend the expertise of ISB
33   Commission 6 substantially by COST (A European programme of promoting Cooperation in
34   Science and Technology) Action 730 so that ultimately, for ISB and COST together, over 45
35   scientists from 23 countries (Australia, Canada, Europe, Israel, New Zealand, and the USA

worked together. The work was done under the umbrella of WMO- Commission on Climatology CCl.

After extensive evaluations Fiala's multi-node human Physiology and thermal Comfort model (FPC) was adopted for this study. The model was extensively validated applying as yet unused data from other research groups, and extended for purposes of the project. This model was coupled with a state-of-the-art clothing model considering the behavioural adaptation of clothing insulation by the general urban population to actual environmental temperature. UTCI was then derived conceptually as an Equivalent Temperature (ET). Thus, for any combination of air temperature, wind, radiation, and humidity (stress), UTCI is defined as the air temperature of the reference condition which would elicit the same dynamic response (strain) of the physiological model as the actual conditions. As UTCI is based on contemporary science its use will standardize applications in the major fields of human biometeorology thus making research results comparable and physiologically relevant.

Keywords: Outdoor climate, Thermal assessment, Index, Thermal stress, Thermo-physiology, Model

Introduction

The close relationship of humans to the thermal component of the atmospheric environment is self-evident and belongs to everybody's daily experience. Thus, issues related to thermal comfort, discomfort, and health impacts are the reason that the assessment and forecast of the thermal environment is one of the fundamental and enduring themes within human biometeorology. In this context the term "thermal environment" encompasses both the atmospheric heat exchanges with the body (stress) and the body's physiological response (strain).

The following fields of applications are considered as particularly significant for users:

1) <u>Public weather service (PWS)</u>. The issue is how to inform and advice the public on thermal conditions at a short time scale (weather forecast) for outdoor activities, appropriate behaviour, and climate-therapy. Currently various national meteorological services around the world are using a plethora of indices in their public weather

2) <u>Public health system (PHS)</u>. In order to mitigate adverse health effects by extreme weather events (here heat waves and cold spells) it is necessary to implement appropriate disaster preparedness plans. This requires warnings about extreme thermal stress so that interventions can be released in order to save lives and reduce health impacts.

3) <u>Precautionary planning</u>. This refers to a wide range of applications in public and individual precautionary planning such as urban and regional planning, and in the tourism industry. The increasing reliability of monthly or seasonal forecasts should be considered to help develop appropriate operational products.

4) <u>Climate impact research in the health sector</u>. The increasing awareness of climate change and therewith related health impacts requires epidemiological studies based on cause-effect related approaches.

Balancing the human heat budget, i.e. equilibration of the organism to variable environmental (atmospheric) and metabolic heat loads is controlled by a very efficient (for healthy people) autonomous thermoregulatory system. This is additionally supported by behavioural adaptation (e.g. eating and drinking, activity and resting, clothing, exposure, housing, migration) which is driven by conscious sensations of thermal discomfort. These capabilities enable the (healthy) human being to live and to work in virtually any climate zone on earth, albeit with varying degrees of discomfort.

The heat exchange between the human body and its environment takes place by sensible and latent heat fluxes, radiation and (generally negligible) conduction. Comprehensively characterising the thermal environment in thermo-physiologically significant terms requires application of a complete heat budget model that takes all mechanisms of heat exchange into account (Büttner, 1938; Parsons, 2003). Atmospheric environmental parameters governing all of the abovementioned heat exchanges include air temperature, water vapour pressure, wind velocity, mean radiant temperature including the short- and long-wave radiation fluxes of the atmosphere (see Weihs et al., 2011 elsewhere in this issue), in addition to metabolic rate and clothing insulation worn by the subject. Only thermal climate indices that incorporate all of the parameters of the human heat budget can be universally utilised across the full gamut of

1 biometeorological applications, across all climate zones, regions and seasons (e.g. Jendritzky

2 and de Dear, 2009).

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4 In recognition that the human thermal environment cannot be represented adequately with just

5 a single parameter, air temperature (T_a), over the last 150 years or so more than 100 simple

6 thermal indices have been developed, most of them two-parameter indices. For warm

7 conditions such indices usually consist of combinations of T_a and one of a variety of

8 expressions for humidity, while for cold conditions the combination typically consists of T_a

9 combined in some way with air speed (v). Simple indices are easy to calculate and therefore

10 easy to forecast. In addition they are readily communicated to the general public and

11 stakeholders such as health service providers (Koppe et al., 2004). However, due to their

12 simple formulation, i.e. neglecting significant fluxes or variables, these indices can never

13 fulfil the essential requirement that for each index value there must always be a corresponding

14 and unique thermo-physiological state (strain), regardless of the combination of the

15 meteorological input values (stress). Simple indices can only be of limited value, results are

16 often not comparable and often lead to misrepresentations of the thermal environment, and

17 additional features such as safety thresholds have to be defined arbitrarily and cannot be

18 transferred to other locations.

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20 These inadequacies of two-parameter indices have prompted hundreds of attempts at

21 improvement The Wind-Chill Temperature (ISO 11079, 2007) and subsequently the New

22 Wind Chill Index (Osczevski and Bluestein, 2005) are illustrative in this regard; the turbulent

23 heat flux is disproportionate and has been critiqued by Shitzer (2006) and Shitzer and de Dear

24 (2006). In occupational health the Wet Bulb Globe Temperature (WBGT, ISO 7243, 1989)

25 evolved in the 1950s, but is still popular for considerations of humidity and thermal radiation

26 in warm environments. Comprehensive reviews of simple indices can be found in e.g., Fanger

27 (1970), Landsberg (1972), Driscoll (1992), and Parsons (2003).

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29 During the last 40 years thermal biomereorology advanced significantly with the development

30 of heat budget models (see Stollwijk, 1971 and related 2-node model associated with Gagge

31 et al, 1986). Subsequent developments, still relatively simple, include models such as MEMI

32 with the output of PET (Höppe, 1984, 1999; Matzarakis et al., 2007), and the Outdoor

Apparent Temperature[1] (Steadman 1984, 1994). More comprehensive models and indices based upon the human heat balance equation include the Standard Effective Temperature (SET*) index (Gagge et al. 1986), and OUT_SET* (Pickup and De Dear 2000; De Dear and Pickup 2000), which translates Gagge's indoor version of the index to an outdoor setting by simplifying the complex outdoor radiative environment down to a mean radiant temperature (T_{mrt}). Blazejczyk (1994) presented the man-environment heat exchange model MENEX, while the extensive work by Horikoshi et al. (1995, 1997) resulted in a Thermal Environmental Index. While the aforementioned heat budget models are applicable across the full range of heat exchange conditions, the Predicted Heat Strain (PHS, ISO 7933, 2004) which is used in occupational medicine, is relevant only to warm environments.

Fanger's (1970) PMV (Predicted Mean Vote) equation can also be included among the advanced heat budget models if the improvement by Gagge et al. (1986) in the description of latent heat fluxes by the introduction of PMV* is applied. This approach is generally the basis for the operational thermal assessment procedure Klima-Michel-Model KMM (Jendritzky et al. 1979, 1981; Jendritzky, 1990) of the German national weather service DWD (Deutscher Wetterdienst) with the output parameter "Perceived Temperature (PT)" (Staiger et al. 1997; VDI 2008) that considers behavioural adaptation by varying clothing. For more than two decades KMM was the sole assessment procedure which has included a complete radiation model to calculate Tmrt on basis of meteorological data. To date the German weather service (DWD) is the only national weather service to run a complete heat budget model (KMM-PT) on a routine basis specifically for applications in human biometeorology.

Although each of the heat budget models referred to above is, in principle, appropriate for use in any kind of assessment of the thermal environment, none of them is accepted as a fundamental standard, neither by researchers nor by end-users. This is probably because of persistent shortcomings in relation to thermo-physiology and heat exchange theory. On the other hand, it is surprising that after 40 years experience with heat budget modelling and easy access both to computational power and meteorological data, the crude and basic empirical indices like WBGT actually are still widely used. For comparisons of both selected simple indices and also of more complex heat budget based approaches to the creation of a Universal

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[1] The Indoor AT, which forms the basis of the US Heat Index, often used in outdoor applications by neglecting the prefix "Indoor" belongs to the simple two-parameter indices.

Thermal Climate Index (UTCI) see Blazejczyk et al. (2011) and Kampmann and Bröde (2009 and 2011 elsewhere in this issue).

A decade ago the International Society on Biometeorology ISB recognised these shortcomings in thermal indices and established the Commission 6 "On the development of a Universal Thermal Climate Index UTCI" (Jendritzky et al., 2002). Since 2005 these efforts have been reinforced by the COST Action 730 (Cooperation in Science and Technology, supported by the EU RTD Framework Programme) that provided ultimately the basis for scientists from 23 countries (18 from Europe plus experts from Australia, Canada, Israel, New Zealand, and the USA) to collaborate on development of such an index (COST UTCI, 2004). The aim was an international standard based on the latest scientific progress in human response related thermo-physiological modelling of the last four decades. The term "universal" must be understood in terms of being appropriate for all assessments of outdoor thermal conditions in major human biometeorological applications such as daily forecasts and warnings of extreme weather, bioclimatic mapping, urban and regional planning, environmental epidemiology and climate impacts research. This covers the fields of public weather service, the public health system, precautionary planning, and climate impact research in the health sector.

The Universal Thermal Climate Index UTCI must meet the following requirements:

1) Thermo-physiologically responsive to all modes of heat exchange between body and environment.
2) Applicable for whole-body calculations but also for local skin cooling (frostbite) (see Shitzer and Tikusis (2011) elsewhere in this issue)
3) Valid in all climates, seasons, and time and spatial scales
4) Appropriate for key applications in human biometeorology (listed above)

Approach and results

Thermoregulation

For the human being it is crucial to keep the body's core temperature within a narrow range around 37°C, in order to ensure functioning of the inner organs and of the brain. In contrast the temperature of the shell, i.e. skin and extremities, can vary significantly depending on the

volume of blood it contains, which in turn depends on metabolic and environmental heat loads. Heat is produced by metabolism as a result of activity, sometimes increased by shivering or slightly offset by mechanical work where applicable, e.g. when climbing. The heat must be released to the environment by convection (sensible heat flux), conduction (contact with solids), evaporation (latent heat flux), radiation (long- and short-wave), and respiration (latent and sensible).

From the analytical point of view, the human thermoregulatory system can be separated into two interacting sub-systems: (1) the controlling active system which includes the thermoregulatory responses of shivering [thermo genesis] sweat moisture excretion, and peripheral blood flow regulation (Fig. 1a), and (2) the controlled, passive system dealing with the physical human body and the heat transfer occurring within it and at its surface (Fig. 1b). This accounts for local heat losses from body parts by free and forced convection, long-wave radiation exchange with surrounding surfaces, solar irradiation, and evaporation of moisture from the skin and heat and mass transfer through non-uniform clothing. Under comfort conditions the active system shows the lowest activity level indicating no strain. Increasing discomfort is associated with increasing strain and related impacts on the cardiovascular and respiratory system. The tolerance to thermal extremes depends on personal characteristics (Havenith 2001, 2005): age, fitness, gender, acclimatization, morphology, and fat thickness being among the most significant. Of these, age and fitness are the most important predictors and both are closely correlated. High age and/or low fitness level are associated with low cardiovascular reserve which causes low thermal tolerance.

Figure 1 a,b   Schematic representation of human physiological and behavioural
                 thermoregulation (after Havenith 2001, Fiala et al. 2001)

The heat budget

The heat exchange between the human body and the thermal environment (Fig. 2) can be described in the form of the energy balance equation (Eq. 1); essentially the first theorem of thermodynamics applied to the body's heat sources (metabolism and environmental), and the various avenues of heat loss to environment (Büttner 1938):

1    $M - W - [Q_H(T_a, v) + Q^*(T_{mrt})] - [Q_L(e, v) + Q_{SW}(e, v)] - Q_{Re}(T_a, e) \pm S = 0$ Eq. 1

2   *M*   Metabolic rate (activity)

3   *W*   Mechanical power

4   *S*   Storage (change in heat content of the body)

5   **Peripheral (skin) heat exchanges:**

6   Q_H Turbulent flux of sensible heat

7   Q^* Radiation budget

8   Q_L Turbulent flux of latent heat (passive diffusion water vapour through the skin)

9   Q_{SW} Turbulent flux of latent heat (sweat evaporation)

10   **Respiratory heat exchanges:**

11   Q_{Re} Respiratory heat flux (sensible and latent)

12   **Thermal environmental parameters:**

13   T_a Air temperature

14   T_{mrt} Mean temperature

15   *v*   Air speed relative to the body

16   *e*   Partial vapour pressure

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18 The meteorological input variables include air temperature T_a , water vapour pressure *e*, wind

19 velocity *v*, mean radiant temperature T_{mrt} including short- and long-wave radiation fluxes, in

20 addition to metabolic rate and clothing insulation. In eq. 1 the appropriate meteorological

21 variables are attached to the relevant fluxes. However, the internal (physiological) variables

22 (Fig. 1), such as the temperature of the core and the skin, sweat rate, and skin wettedness

23 interacting with the environmental heat exchange conditions are not explicitly mentioned

24 here.

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26 Figure 2   The human heat budget (Havenith 2001)

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29 Mathematical modeling of the human thermal system goes back 70 years. In the past four

30 decades more detailed, multi-node models of human thermoregulation have been developed,

31 e.g. Stolwijk (1971), Konz et al. (1977), Wissler (1985), Fiala et al. (1999, 2001), Huizenga et

32 al. (2001) and Tanabe et al. (2002). These models simulate phenomena of human heat

33 transfers within the body and at its surface, taking into account the anatomical, thermal and

34 physiological properties of the human body (see Fig 1). Environmental heat losses from body

parts are modeled considering the inhomogeneous distribution of temperature and thermoregulatory responses over the body surface. Besides overall thermo-physiological variables, multi-segmental models are capable of predicting 'local' characteristics such as skin temperatures of individual body parts. Validation studies have shown that recent multi-node models accurately reproduce the human dynamic thermal responses over a wide range of thermal circumstances (Fiala et al. 2001, 2003; Havenith 2001, Huizenga et al. 2001). These models have become valuable research tools contributing to a deeper understanding of the principles of human thermoregulation.

Modelling

As the assessment of thermal stress should ultimately be based on the physiological response of the human body (thermal strain), ISB Commission 6 decided from the outset that this was to be simulated by one of the most advanced (multi-node) thermo-physiological models. After accessible models of human thermoregulation had been evaluated (Fiala et al. 1999; Tanabe et al. 2002), the Fiala's multi-node human Physiology and thermal Comfort (FPC) model (Fiala et al., 1999; 2001; 2003; 2010) was adopted for this study, extensively validated (Psikuta, 2009; Psikuta et al., 2007; see also Psikuta et al. 2011 elsewhere in this issue), and extended for purposes of the project (Fiala et al., 2007; see also Fiala et al. 2011 elsewhere in this issue).

The passive system of the Fiala model (Fiala et al. 1999, 2001) consists of a multi-segmental, multi-layered representation of the human body with spatial subdivisions. Each tissue node is assigned appropriate thermo-physical and thermo-physiological properties. The overall data replicates an average person with respect to body weight, body fat content, and Dubois surface area. The physiological data aggregates to a basal [whole body] heat output and basal cardiac output, which are appropriate for a nude, reclining adult in a thermo-neutral environment of 30°C. In these conditions, where thermoregulatory activity is minimal, the model predicts a basal skin wettedness of 6%; a mean skin temperature of 34.4°C; and body core temperatures of 37.0°C in the head core (hypothalamus) and 36.9°C in the abdomen core (rectum) (Fiala et al. 1999). Verification and validation work using independent experiments from air exposures to cold stress, cold, moderate, warm and hot stress conditions, and a wide range of exercise intensities revealed good agreement with measured data for regulatory responses, mean and local skin temperatures, and internal temperatures across the whole

spectrum of boundary conditions considered (Richards and Havenith 2007). By including as yet unused data from other research groups the Fiala human Physiology and thermal Comfort (FPC) model (Fiala et al. 2010) could be substantially advanced. FPC was adopted by the ISB Commission 6 as the benchmark ("most advanced") in terms of thermo-physiology and heat exchange theory.

In the next step a state-of-the-art adaptive clothing model was developed and integrated (Richards and Havenith, 2007; Havenith et al. 2011 elsewhere in this issue). This model considers

1) the behavioural adaptation of clothing insulation observed for the general urban population in relation to the actual environmental temperature,

2) the distribution of the clothing over different body parts providing local insulation values for the different anatomical segments, and

3) the reduction of thermal and evaporative clothing resistances caused by wind and limb movements of the wearer, who was assumed to be walking at a speed of 4 km/h on level ground (2.3 MET = 135 W/m²).

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 20 hPa), with calm 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, and 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). 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. As calculating the UTCI equivalent temperatures by repeatedly running the thermoregulation model could be too time-consuming for climate simulations and numerical weather forecasts, a fast calculation procedure has been developed and made available (for details see Bröde et al. 2008; 2009a; Bröde et al. 2011 elsewhere in this issue).

Conclusion

The main objective of this collaboration between 45 scientists from 23 countries was to develop a readily accessible thermal index based on a state-of-the-art thermo-physiological model. The UTCI resulting from this research is intended to significantly enhance applications related to human health and well-being in the fields of public weather services, public health systems, precautionary planning, and climate impact research. The development of UTCI required cooperation of experts from diverse disciplines including thermo-physiology, occupational medicine, physics, meteorology, biometeorological and environmental sciences. After many decades of frustrating attempts by individual researchers working on thermal indices in isolation from cognate disciplines, the UTCI team's multidisciplinary approach facilitated the research synergies necessary for a universal solution to the problem of characterising the human thermal environment. Embedding the UTCI project within a Commission of the International Society of Biometeorology and also a European COST Action provides an international framework for this new climatic index to evolve into a methodological standard.

The Universal Thermal Climate Index UTCI assesses the outdoor thermal environment for biometeorological applications by simulating the dynamic physiological response with a model of human thermoregulation coupled with a state-of-the-art clothing model. The operational procedure (available as software from the UTCI website http://www.utci.org) shows plausible responses to humidity and radiative loads in hot environments, as well as to wind in the cold. UTCI was in good agreement with the assessment of other standards concerned with the thermal environment (Psikuta et al. 2011 elsewhere in this issue). Local cooling of exposed skin, including frostbite risk (wind chill effects), should best be regarded as a transient, rather than a steady-state phenomenon (Shitzer, 2006; Tikuisis and Osczevski, 2002, 2003). The consensus final procedure for cold exposure using UTCI, however, still remains to be determined (Shitzer and Tikuisis, 2011 elsewhere in this issue).

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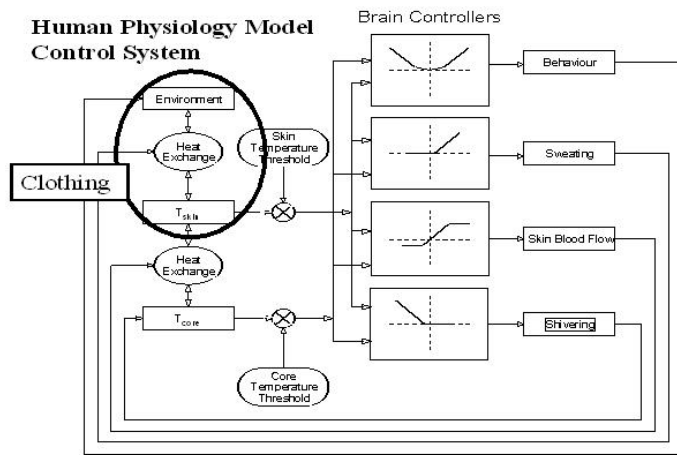
Figures

Figure 1 a, b   Schematic representation of human physiological and behavioural thermoregulation (after Havenith 2001, Fiala et al. 2001).
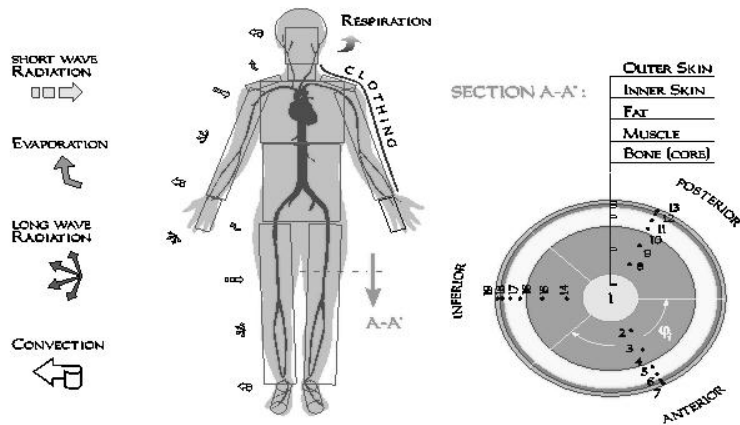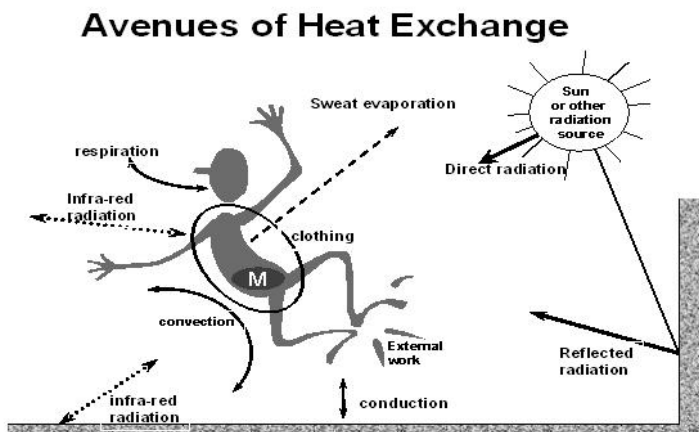
Figure 2   The human heat budget (Havenith 2001).

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Figure 1a

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Figure 1b

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Figure 2

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