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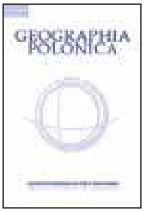

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AN INTRODUCTION TO THE UNIVERSAL THERMAL CLIMATE INDEX (UTCI)

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Abstract

The assessment of the thermal environment is one of the main issues in bioclimatic research, and more than 100 simple bioclimatic indices have thus far been developed to facilitate it. However, most of these indices have proved to be of limited applicability, and do not portray the actual impacts of thermal conditions on human beings. Indices derived from human heat-balance models (one- or two-node) have been found to offer a better representation of the environmental impact in question than do simple ones. Indeed, the new generation of multi-node models for human heat balance do allow full account to be taken of heat transfer and exchange, both within the human body and between the body surface and the surrounding air layer. In this paper, it is essential background information regarding the newly-developed Universal Thermal Climate Index *UTCI* that is presented, this in fact deriving from the Fiala multi-node model of human heatbalance. The *UTCI* is defined as the air temperature (*Ta*) of the reference condition causing the same model response as actual conditions. *UTCI* was developed in 2009 by virtue of international co-operation between leading experts in the areas of human thermophysiology, physiological modelling, meteorology and climatology. The necessary research for this had been conducted within the framework of a special commission of the International Society of Biometeorology (ISB) and European COST Action 730.

Key words

UTCI • human heat balance • multi-node model • bioclimatic index • International Society of Biometeorology • COST Action 730

Introduction

The matter of the thermal environment's being assessed in an effective and practical way is a fundamental one for human biometeorology, due to its being of key importance in research on thermal comfort, discomfort, and health impacts. The term 'biothermal environment' encompasses consideration of both atmospheric heat exchange conditions (stress), and physiological responses (strain). The balancing of the human heat budget, i.e. equilibration of the thermal state of an organism to variable atmospheric heat exchange conditions is controlled by a very efficient autonomous thermoregulatory system that is additionally supported by behavioural adaptation, as controlled by discomfort sensations (Błażejczyk 2004; Błażejczyk & Kunert 2011; IUPS 2003; Havenith 2001; Parsons 2003).

In 1999, the International Society of Biometeorology (ISB) established a Commission 'On the development of a Universal Thermal Climate Index *UTCI*'. The goal of this project was to derive a thermal index based on the most advanced thermophysiological model. Since 2005, these efforts have been reinforced by European COST (Cooperation in Science and Technical Development) Action 730, which has brought together leading experts in the areas of human thermophysiology, physiological modelling, meteorology and climatology, with a view to the Universal Thermal Climate Index, *UTCI,* being developed. In 2009, COST Action 730 was brought to a successful close, since the *UTCI* has been developed. This paper seeks to introduce the principles that underpin it, while this issue of Geographia Polonica also offers an example of the *UTCI* being applied in bioclimatic research.

Principles underpinning *UTCI*

Applications in human biometeorology require that there be thermophysiologically relevant assessments of the atmospheric environment. Although various models are available today, they are either not accepted generally, or deemed to be of restricted validity, due to the range of environmental conditions being limited.

The general idea regarding *UTCI* deliverables was thus to entail goal-setting and attainment as regards:

- thermo-physiological significance across the entire range of heat exchange.
- applicability to whole-body calculations, but also local skin cooling (as in frost bite, for example).
- validity in all climates and seasons, as well as on spatial and temporal scales from the micro through to the macro.
- usefulness for key applications in human biometeorology, for example in the Public Weather Service, Public Health Service, precautionary planning and climate impact research.
- representation as a temperature-scale index.

Physiological background

It is crucial for a human being that his/her core body temperature be maintained within a narrow range either side of 37°C, in order that functioning of the inner organs and brain may be assured, with attendant optimisation of comfort, performance and health. In contrast, the temperature of the shell, i.e. the skin and extremities, is allowed to vary wildly, depending on the environmental conditions, this being one of the mechanisms maintaining equilibrium as regards heat production and heat loss, at least over a longer period, in this way reducing changes in heat content in the body (S) to zero. Heat is produced by metabolism (M) and any muscular activity (W). The surplus heat must be released to the environment. The heat can be exchanged by convection (sensible heat flux – C), conduction (contact with solids – K), evaporation (latent heat flux – E), radiation (long- and short-wave – Q), and respiration (latent and sensible – Res). The heat exchange between the human body and the environment can then be described in the form of the energy balance equation:

$$M + W + C + K + E + Q + Res \pm S = 0 \quad (1)$$

Following the pioneering work of Stolwijk (1971), a number of multi-segmental thermoregulatory models were developed (Fiala et al. 1999, 2001, 2003; Huizenga et al. 2001; Tanabe et al. 2002). After several evaluations, the advanced multi-node 'Fiala' thermoregulation model was selected, this also providing for predicted votes of the dynamic thermal sensation based on core and skin temperature signals. Under COST Action 730, the physiological model was validated extensively (Psikuta et al. 2012), before being adapted and extended for the purposes of the project (Fiala et al. 2012).

The *UTCI*-Fiala model

In the Fiala model, the human organism is separated into two interacting systems of thermoregulation, i.e. (1) the controlling active system, and (2) the controlled passive system. The model furthermore incorporates a thermal comfort model which predicts human perceptual responses dynamically from physiological states.

The passive system is a multi-segmental, multilayered representation of the human body with information on anatomical and physiological body properties. The model represents an average person with a body weight of 73.5 kg, body fat content of 14%, and Dubois-area of 1.86 m^2. The body is idealised as spherical and cylindrical elements built of annular concentric tissue layers with appropriate thermophysical properties and physiological functions (Fiala et al. 1999). Body elements are further subdivided into spatial sectors and into individual tissue nodes. The passive system of the *UTCI* model version consists of 12 body elements comprising 187 tissue nodes in total.

The active system of the '*UTCI*-Fiala' model predicts the thermoregulatory reactions of the central nervous system, i.e. the suppression (vasoconstriction) and elevation (vasodilatation) of the cutaneous blood flow, shivering thermogenesis, and sweat moisture excretion. The active system was developed by means of statistical regression (Fiala et al. 2001), using measured data obtained from a variety of physiological experiments covering steady-state and transient cold stress; cold, moderate, warm and hot stress conditions; and activity levels up to heavy exercise.

Definition of the *UTCI*

The *UTCI* is defined as the air temperature (*Ta*) of the reference condition causing the same model response as actual conditions. The offset, i.e. the deviation of *UTCI* from air temperature, depends on the actual values of air and mean radiant temperature (*Tmrt*), wind speed (*va*) and humidity, expressed as water vapour pressure (*vp*) or relative humidity (*RH*) (Fig. 1). This may be written in mathematical terms as

$$UTCI = f\,(Ta;\ Tmrt;\ va;\ vp) = \\ = Ta + \text{Offset}\,(Ta;\ Tmrt;\ va;\ vp) \qquad (2)$$

Reference condition

Application of this characterisation requires that both the reference condition and the dynamic model response be identified. To convert climate impact to a single value, and to facilitate the interpretation and understanding of the *UTCI*, reference conditions must be (1) defined in terms conforming to most people's experiences, and (2) relevant across the whole spectrum of climate zones to which the *UTCI* is going to be applied. Therefore, the non-meteorological variables metabolic rate MET and the thermal properties of clothing (insulation, vapour resistance, air permeability) are of great importance. In 2000, the ISB Commission on the *UTCI* defined representative outdoor activity as a person walking at a 4 km per hour ($\cong$1.1 $m \cdot s^{-1}$). So, the rate of metabolic heat production was assumed to be 2.3 MET ($\cong$135 $W \cdot m^{-2}$).

For the reference environment, it was decided to use:

- a wind speed (*va*) of $\cong$0.5 $m \cdot s^{-1}$ at 10 m height (approximately $\cong$0.3 $m \cdot s^{-1}$ at 1.1 m),
- a mean radiant temperature (*Tmrt*) equal to air temperature,
- vapour pressure (*vp*) that represents a relative humidity of 50%; at high air temperatures (>29°C) the reference humidity was taken to be constant at 20 hPa.

Statistical modelling of *UTCI*

The *UTCI* ultimately aims to be a one-dimensional quantity adequately reflecting the human physiological reaction to the actual thermal condition as defined multi-dimensionally. As Figure 1 shows, the index value will be calculated in relation to the multivariate dynamic output of that model.

The characterisation of the model response should be indicative for the physiological and thermoregulatory processes as listed in Table 1, which are significant for the human reaction to neutral, moderate and extreme thermal conditions (Bröde et al. 2012; Kampmann et al. 2008).

The offsets of *UTCI* to *Ta* were approximated by a polynomial in *Ta*, *va*, *vp*, *Tmrt-Ta* including all the main effect and interaction terms up to the 6th order. The least-squares estimates of the 210 coefficients were found (Błażejczyk et al. 2010; Błażejczyk & Kunert 2011). The root mean squared error was 1.1°C, 50% of all observed errors were

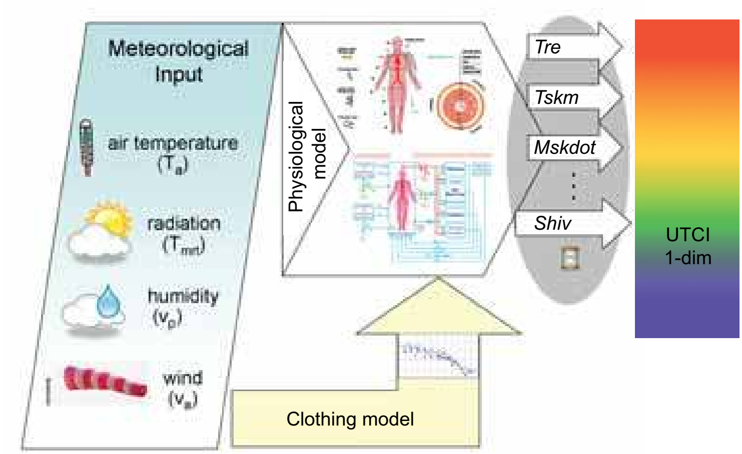

Figure 1. Concept of the *UTCI* derived as equivalent temperature from the dynamic multivariate response of the thermophysiological *UTCI*-Fiala model (Fiala et al. 2012), which was coupled with a clothing model (Havenith et al. 2012).

Table 1. Variables available from the output of the thermophysiological model after exposure times of 30 and 120 min.

Variable	Abbreviation	Unit
Rectal temperature	*Tre*	°C
Mean skin temperature	*Tskm*	°C
Face skin temperature	*Tskfc*	°C
Sweat production	*Mskdot*	g/min
Heat generated by shivering	*Shiv*	W
Skin wettedness	*wettA*	% of body area
Skin blood flow	*VblSk*	% of basal value

within ±0.6°C, 80% within ±1.3°C, and 90% within ±1.9°C. For operational use, a FORTRAN subroutine computing *UTCI* values on an ordinary desktop computer was implemented. The *UTCI* is also implemented to the *BioKlima 2.6.* software package (http://www.igipz.pan.pl/Bioklima-zgik.html).

The assessment scale of the *UTCI*

The different values of the *UTCI* are categorized in terms of thermal stress. The present approach looks at responses to reference conditions and deducts the load (i.e. the heat or cold stress) caused by the organism's physiological response to actual environmental conditions. Table 2 pre-

Table 2. *UTCI* equivalent temperature categorized in terms of thermal stress.

UTCI (°C) range	Stress Category	Physiological responses
above +46	extreme heat stress	– increase in *Tre* time gradient – steep decrease in total net heat loss – averaged sweat rate >650 g/h, steep increase
+38 to +46	very strong heat stress	– core to skin temperature gradient < 1K (at 30 min) – increase in *Tre* at 30 min
+32 to +38	strong heat stress	– dynamic Thermal Sensation (DTS) at 120 min >+2 – averaged sweat rate > 200 g/h – increase in *Tre* at 120 min – latent heat loss >40 W at 30 min – instantaneous change in skin temperature > 0 K/min
+26 to +32	moderate heat stress	– change of slopes in sweat rate, *Tre* and skin temperature: mean (*Tskm*), face (*Tskfc*), hand (*Tskhn*) – occurrence of sweating at 30 min – steep increase in skin wettedness

UTCI (°C) range	Stress Category	Physiological responses
+9 to +26*	no thermal stress	– averaged sweat rate > 100 g/h – DTS at 120 min < 1 – DTS between -0.5 and +0.5 (averaged value) – latent heat loss >40 W, averaged over time – plateau in *Tre* time gradient
+9 to 0	slight cold stress	– DTS at 120 min < -1 – local minimum of *Tskhn* (use gloves)
0 to -13	moderate cold stress	– DTS at 120 min < -2 – skin blood flow at 120 min lower than at 30 min (vasoconstriction) – averaged *Tskfc* < 15°C (pain) – decrease in *Tskhn* – *Tre* time gradient < 0 K/h – 30 min face skin temperature < 15°C (pain) – *Tmsk* time gradient < -1 K/h (for reference)
-13 to -27	strong cold stress	– averaged *Tskfc* < 7°C (numbness) – *Tre* time gradient < -0.1 K/h – *Tre* decreases from 30 to 120 min – increase in core to skin temperature gradient
-27 to -40	very strong cold stress	– 120 min *Tskfc* < 0°C (frostbite) – steeper decrease in *Tre* – 30 min *Tskfc* < 7°C (numbness) – occurrence of shivering – *Tre* time gradient < -0.2 K/h – averaged *Tskfc* < 0°C (frostbite). – 120 min *Tskfc* < -5°C (high risk of frostbite)
below -40	extreme cold stress	– *Tre* time gradient < -0.3 K/h – 30 min *Tskfc* < 0°C (frostbite)

* It can be noted that, with respect to the averaged dynamic thermal sensation, *UTCI* values between 18 and 26°C may comply closely with the definition of the '*thermal comfort zone*' supplied in the Glossary of Terms for Thermal Physiology (IUPS 2003) as: *The range of ambient temperatures, associated with specified mean radiant temperature, humidity, and air movement, within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period*.

sents the labelled stress categories and a list of physiological criteria.

The applicability of the *UTCI* was compared with selected biometeorological indices (e.g. Effective Temperature – *TE*, Wet-Bulb Globe Temperature – *WBGT*, Heat Stress Index – *HSI*, Wind Chill Temperature – *WCT*, Perceived Temperature – *PT*, Physiological Equivalent Temperature – *PET*, Standard Effective Temperature – *SET**, Physiological Subjective Temperature – *PST*, and Physiological Strain – *PhS*). The main finding from the comparisons made for various sets of data (global, regional, local, daily and momentary data) was that the *UTCI* offers a better portrayal of biothermal conditions for human beings than do other indices (Błażejczyk et al. 2012).

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author(s), on the basis of their own research.

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