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# PRINCIPLES OF THE NEW UNIVERSAL THERMAL CLIMATE INDEX (UTCI) AND ITS APPLICATION TO BIOCLIMATIC RESEARCH IN EUROPEAN SCALE

**Abstract:** During the last century about 100 indices were developed to assess influences of the atmosphere on human being. However, most of them have not close relationships with physiological reactions in man. In 1999 International Society of Biometeorology established special study group do develop new Universal Thermal Climate Index (UTCI). Since 2005 these efforts have been reinforced by the COST Action 730 (Cooperation in Science and Technical Development). In February 2009 the Action was terminated and UTCI was developed.
The new UTCI index represents air temperature of the reference condition with the same physiological response as the actual condition. The index base on Fiala model that is one of the most advanced multi-node thermophysiological models and include the capability to predict both whole body thermal effects (hypothermia and hyperthermia; heat and cold discomfort), and local effects (facial, hands and feet cooling and frostbite). The model consists of two interacting systems: the controlling active system; and the controlled passive system. The assessment scale of UTCI bases on the intensity of objective physiological reactions to environmental heat stress in wide range of weather and climates. The index can be applicable in various research, for example in weather forecasts, bioclimatological assessments, bioclimatic mapping in all scales (from micro to macro), urban design, engineering of outdoor spaces, consultancy for where to live, outdoor recreation and climatotherapy, epidemiology and climate impact research.
The paper presents thermophysiological principles of UTCI as well as some examples of its application to assess bioclimatic differentiation of Europe.

**Key words**: human heat balance, UTCI, heat stress, Europe's bioclimate.

## INTRODUCTION

The close relationship of humans to the thermal component of the atmospheric environment is evident and belongs to everybody's daily experience. Thus, issues related to thermal comfort, discomfort, and health impacts are the reason that the assessment of the thermal environment in a sound, effective and practical way is one of the fundamental subjects in human biometeorology. Thereby the term "thermal environment" comprises both the consideration of the atmospheric heat exchange conditions (stress) and the physiological response (strain) (Jendritzky et al, eds. 2009).

Balancing the human heat budget, i.e. equilibration of the organism to variable atmospheric heat exchange conditions is controlled by a very efficient autonomous thermoregulatory system that is additionally supported by behavioural adaptation controlled by discomfort sensations (Błażejczyk, 2004; *Glossary…* 2003; Havenith, 2001; Parsons, 2003).

In 1999 the International Society on Biometeorology (ISB) established a commission "On the development of a Universal Thermal Climate Index UTCI" (Jendritzky et al., 2002). The goal of this project was to derive a thermal assessment procedure based on the most advanced thermo-physiological model. Since 2005 these efforts have been reinforced by the European COST Action 730 (Cooperation in Science and Technical Development). The COST Action 730 brought together leading experts in the area of human thermophysiology, physiological modelling, meteorology and climatology to develop the Universal Thermal Climate Index. In 2009 the COST Action 730 was successfully terminated and new UTCI was developed. The aim of the paper is to present principles of UTCI index and an example of its application in bioclimatic research.

## PRINCIPLES OF UTCI

The UTCI is set out to meet the following goals:

1. Thermo-physiologically significant across the entire range of heat exchange.
2. Applicable for whole-body calculations but also for local skin cooling (frost bite).
3. Valid in all climates, seasons, and scales from micro to macro.
4. Useful for key applications in human biometeorology, for example in Public Weather Service, Public Health Service, Precautionary Planning, Climate Impact Research.
5. Represent a temperature-scale index.

## PHYSIOLOGICAL BACKGROUND

Applications in human biometeorology require thermophysiologically relevant assessments of the atmospheric environment. Although various models are available today, they are either not generally accepted or their validity is restricted to a limited range of environmental conditions.

For the human being it is crucial to keep the body core temperature within a narrow range around 37°C in order to ensure functioning of the inner organs and the brain, thus optimising its comfort, performance and health. In contrast the temperature of the shell, i.e. skin and extremities, is allowed to vary wildly, depending on the environmental conditions, which is one of the mechanisms to keep heat production and heat loss, at least over a longer period in equilibrium, i.e. to reduce 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 environment can be described in the form of the energy balance equation:

$$M + W + C + K + E + Q + Res \pm S = 0$$

Mathematical modelling of the human thermal system goes back 70 years. Most of the work has been accomplished in the area of occupational medicine, occupant comfort and indoor climate design in artificial, man-made spaces, e.g. Outdoor Standard Effective Temperature model, SET (Gagge et al., 1986; Pickup and de Dear, 2000); Munich Energy Balance Model of Individuals, MEMI (Höppe, 1984), Man-Environmental Heat Exchange Model, MENEX (Blazejczyk, 1994, 2004), and the required sweat rate approach (ISO 7933). In the past four decades more detailed, multi-node models of human thermoregulation have been developed, e.g. Stolwijk (1971), Wissler (1985), Fiala et al. (1999, 2001, 2003), Huizenga et al. (2001) and Tanabe et al. (2002). These models simulate phenomena of heat transfer inside the human body and at its surface taking into account the anatomical, thermal and physiological properties of the human body. 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 can reproduce the human thermal behaviour over a wide range of thermal circumstances (Fiala et al. 2001, 2003, Havenith, 2001; Huizenga et al. 2001). Following extensive discussions in COST 730 Work Group 1 (WG1) and based on results of validation exercise, the experts concluded that the “UTCI-Fiala” model is suitable for UTCI purposes to predict the average human thermophysiological behaviour over a wide range of outdoor weather conditions. The model has thus been chosen to form the basis of the UTCI index.

## UTCI-FIALA MODEL

A special version of the Fiala multi-node model was set up and made available for purposes of COST Action 730. In this model the human organism can be separated into two interacting systems of thermoregulation: (1) the controlling active system which includes the thermoregulatory responses of shivering thermogenesis, sweat moisture excretion, and skin blood flow (cutaneous vasomotion), and (2) the controlled passive system dealing with the physical human body and the heat transfer occurring in it and at its surface. The model furthermore incorporates a thermal comfort model which predicts human perceptual responses dynamically from physiological states.

The passive system is a multi-segmental, multi-layered representation of the human body with information on anatomic and physiological body properties. The model represents an average person with a body weight of 73.5 kg, body fat content of 14%, 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 subdivided further 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. 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 of up to heavy exercise.

The Fiala model predicts perceptual responses from physiological body states (Fiala et al., 2003). Comfort experiments involving over 2000 male and female subjects, and covering a wide range of static and transient environmental temperatures, relative humidities, and activity levels were used to derive the Dynamic Thermal Sensation, DTS model (based on the seven-point ASHRAE scale running from -3 for cold to +3 for hot).

## DEFINITION OF UTCI

The UTCI is defined as the air temperature (*Ta*) of the reference condition causing the same model response as the actual condition. Thus, UTCI is the air temperature which would produce under reference conditions the same thermal strain as in the actual thermal environment. Both, meteorological and non-meteorological (metabolic rate and thermal resistance of clothing) reference conditions were defined:

– a wind speed (*va*) of 0.5 m/s at 10 m height (approximately 0.3 m/s in 1.1 m),
– a mean radiant temperature (*Tmrt*) equal to air temperature and,
– vapour pressure (*vp*) that represent relative humidity of 50%; at high air temperatures (>29°C) the reference humidity was taken constant at 20 hPa.
– a representative activity to be that of a person walking with a speed of 4 km/h (1.1 m/s). This provides a metabolic rate of 2.3 MET (135 $W \cdot m^{-2}$).

The adjustment of clothing insulation is a powerful behavioral response to changing climatic conditions. Thereby, the philosophy for *UTCI* was to consider seasonal clothing adaptation habits of Europeans based on available data from field surveys in order to obtain a realistic representation of this behavioral action that notably affects the human perception of the outdoor climate. Regression analysis of data from publications (see Jendritzky et al., 2009) plus results of unpublished surveys conducted in Poland and Sweden revealed the overall intrinsic clothing insulation *Icl* to be a function of the ambient air temperature:

$$Icl = 1.374 - 0.013847 \cdot Ta - 0.00043804 \cdot Ta^2 - 0.0000238383 \cdot Ta^3$$

The above model is based on observed data for ambient temperatures down to -20°C. For extreme cold conditions, however, it seems reasonable to assume that people would increasingly use special protective clothing rather than ordinary clothing. The next factor that must be considered is relative wind speed due to body movement because it reduces insulation and influences the physiological responses of the model (Havenith, Nilsson, 2004; Holmér et al., 1999; ISO 9920; ISO 11079). Thus, the clothing model adjustment due to air temperature and wind has the form presented in fig. 1.

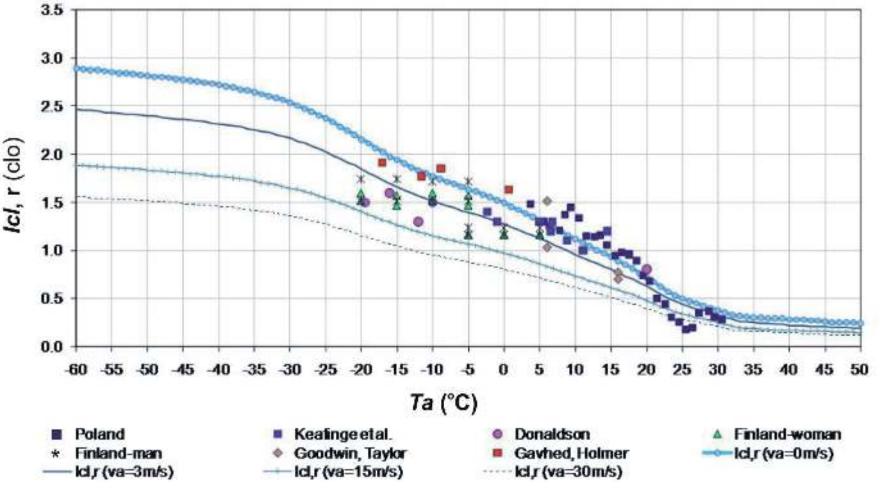



Fig. 1. Global thermal insulation values for different ambient temperature and wind speed (referring to 10 m above the ground): Icl, r = resultant clothing insulation

## STATISTICAL MODELLING OF *UTCI*

The UTCI ultimately aims at developing a one-dimensional quantity which adequately reflects the human physiological reaction to the multi-dimensionally defined actual thermal condition. As illustrated in figure 2, the index value will be calculated from the multivariate dynamic output of that model.

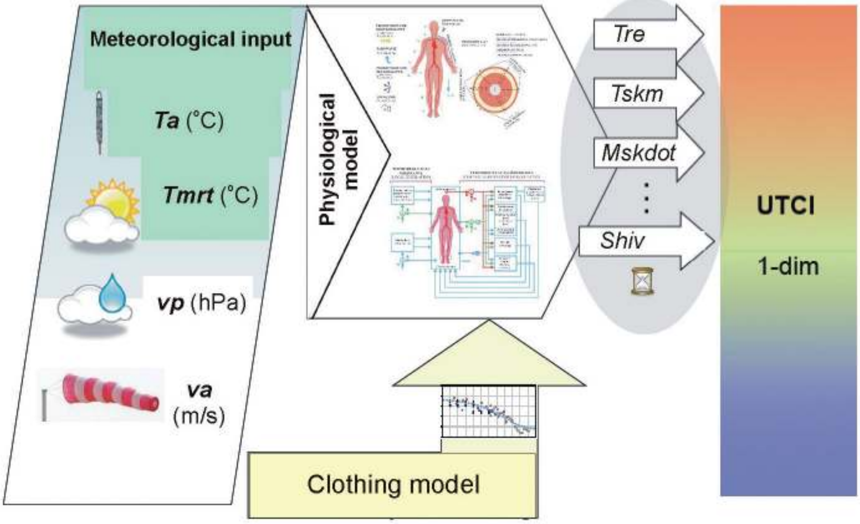



Fig. 2: Scheme for the climatic assessment by UTCI calculated from the dynamic output of a thermophysiological model augmented by a clothing model

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 (Richards, Havenith, 2007; Kampmann et al., 2008).

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 |

In routine applications calculations of UTCI cannot be served by real time execution of the physiological model because of its time-consuming repetition need. Thus, alternative approach – an approximating regression function

– to fast UTCI calculation without the repetitive need to run the actual physiological model but rather using a one off calculation of all relevant conditions was considered and validated.

The offsets of UTCI to *Ta* (UTCI-*Ta*) were approximated by a polynomial in *Ta*, *va*, *vp*, *Tmrt-Ta* including all main effect and interaction terms up to $6^{th}$ order. The least square estimates of the 210 coefficients were found (Jendritzky et al, 2009). The root mean squared error was 1.1°C, 50% of all observed errors were within ±0.6°C, 80% within ±1.3°C, 90% within ±1.9°C. For operational use a FORTRAN subroutine computing *UTCI* values on a common desktop computer was implemented. A special EXCEL worksheet was also prepared, available after contact with authors. UTCI values can be also obtained with the use of BioKlima 2.6. software package (www.igipz.pan.pl/geoekolimat/blaz/BioKlima.htm).

## ASSESSMENT SCALE OF UTCI

Some applications require the categorization of the different values of UTCI in terms of thermal stress. The present approach looks at responses for the reference conditions and deducts load (i.e. heat or cold stress) caused by physiological response of an organism at actual environmental conditions. Table 2 presents the labelled stress categories and a list of physiological criteria.

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 (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*".

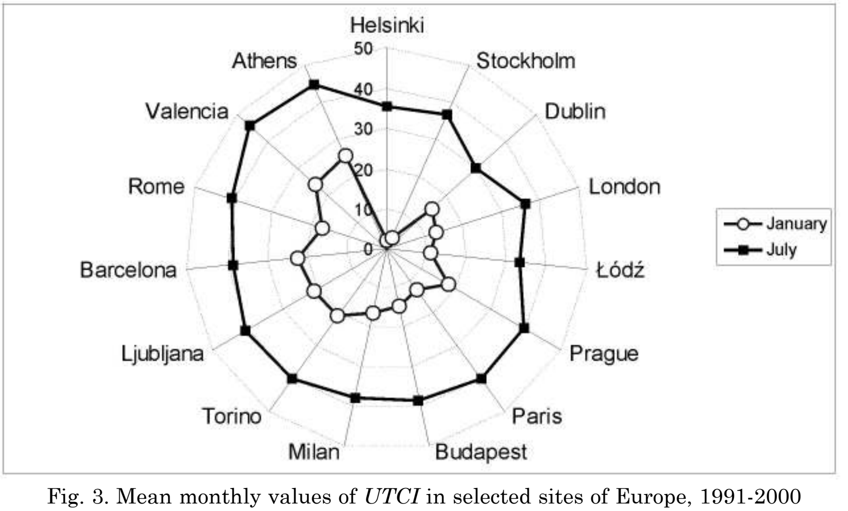



Fig. 3. Mean monthly values of *UTCI* in selected sites of Europe, 1991-2000

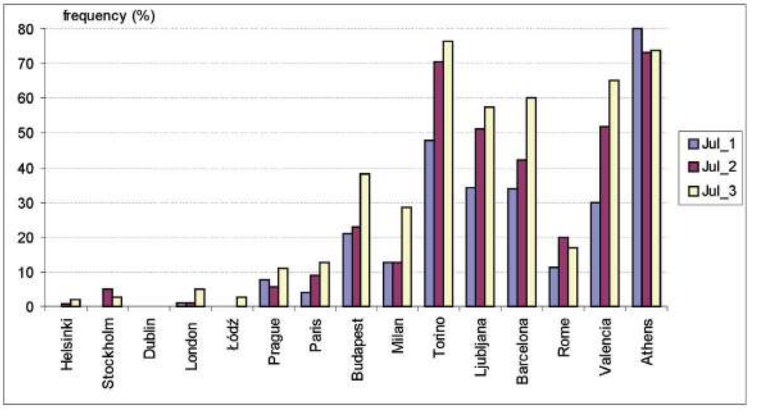
Table 2. UTCI equivalent temperature categorized in terms of thermal stress

| UTCI (°C) range | Stress Category | Physiological responses |
|---|---|---|
| above +46 | extreme heat stress | Increase in *Tre* time gradient.<br>Steep decrease in total net heat loss.<br>Averaged sweat rate >650 g/h, steep increase. |
| +38 to +46 | very strong heat stress | Core to skin temperature gradient < 1K (at 30 min).<br>Increase in *Tre* at 30 min. |
| +32 to +38 | strong heat stress | Dynamic Thermal Sensation (DTS) at 120 min >+2.<br>Averaged sweat rate > 200 g/h.<br>Increase in *Tre* at 120 min.<br>Latent heat loss >40 W at 30 min.<br>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*).<br>Occurrence of sweating at 30 min.<br>Steep increase in skin wettedness. |
| +9 to +26 | no thermal stress | Averaged sweat rate > 100 g/h.<br>DTS at 120 min < 1.<br>DTS between -0.5 and +0.5 (averaged value).<br>Latent heat loss >40 W, averaged over time.<br>Plateau in *Tre* time gradient. |
| +9 to 0 | slight cold stress | DTS at 120 min < -1.<br>Local minimum of *Tskhn* (use gloves). |
| 0 to -13 | moderate cold stress | DTS at 120 min < -2.<br>Skin blood flow at 120 min lower than at 30 min (vasoconstriction).<br>Averaged *Tskfc* < 15°C (pain).<br>Decrease in *Tskhn*.<br>*Tre* time gradient < 0 K/h.<br>30 min face skin temperature < 15°C (pain).<br>*Tmsk* time gradient < -1 K/h (for reference). |
| -13 to -27 | strong cold stress | Averaged *Tskfc* < 7°C (numbness).<br>*Tre* time gradient < -0.1 K/h.<br>*Tre* decreases from 30 to 120 min.<br>Increase in core to skin temperature gradient. |
| -27 to -40 | very strong cold stress | 120 min *Tskfc* < 0°C (frostbite).<br>Steeper decrease in *Tre*.<br>30 min *Tskfc* < 7°C (numbness).<br>Occurrence of shivering.<br>*Tre* time gradient < -0.2 K/h.<br>Averaged *Tskfc* < 0°C (frostbite).<br>120 min *Tskfc* < -5°C (high risk of frostbite). |
| below -40 | extreme cold stress | *Tre* time gradient < -0.3 K/h.<br>30 min *Tskfc* < 0°C (frostbite). |

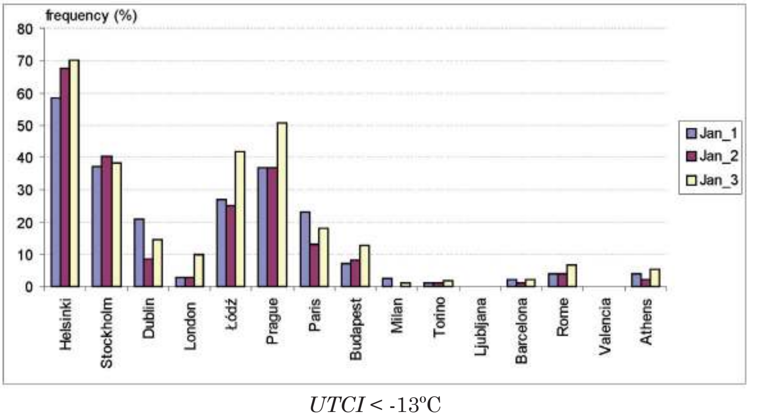
## ASSESSMENT OF BIOCLIMATIC CONDITION OVER EUROPE

Figure 3 shows mean monthly values of UTCI for January and July in selected European cities. As was expected, in both compared months the highest UTCI is observed in Athens (Greece) and Valencia (Spain). In Scandinavian cities (Stockholm and Helsinki) the UTCI is the lowest, especially in January. Low index values are also noted in Łódź (Poland) and London (UK).

We also compared the frequency of extreme *UTCI* values: >32°C in July and <-13°C in January. The results show clear spatial distribution of such situations. In summer strong heat stress is very frequently observed not only in Mediterranean but also in Budapest. Exceptions are Ljubljana (due to it elevation) and Barcelona (due to its costal location). In the Scandinavian cities and in the cities under frequent influence of maritime climate, strong heat stress is very rare. In winter the influence of arctic climate is manifested by frequent occurrence of strong cold stress in Northern and Central Europe. Atlantic Ocean significantly reduces cold stress in London and Dublin (Fig. 4).



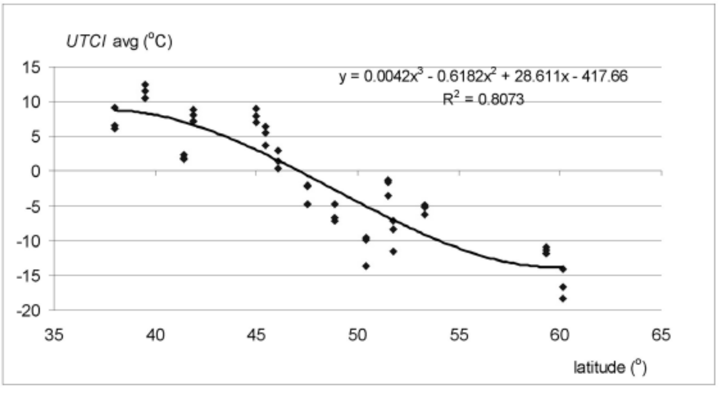

*UTCI* > 32°C



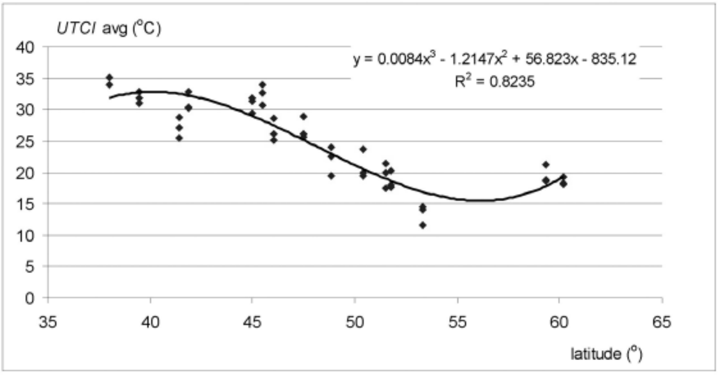

*UTCI* < -13°C

Fig. 4. The frequency of extreme biothermal conditions in selected cities

Following spatial patterns discussed above we have found geographical gradients of UTCI. Both, in January and July mean decadal UTCI significantly depended on latitude. More then 80% of UTCI variations can be explain by this single geographical variable. UTCI values decrease due to the increase of the latitude. In January the difference between Northern and Southern locations is about 25°C and in July about 20°C. It illustrates great spatial variation of biothermal conditions over Europe (Fig. 5).




January




July

Fig. 5. Relationships between latitude and mean decadal *UTCI* values (UTCI avg) in January and July, 1991-2000

## CONCLUSIONS

Accessible models of human thermoregulation were extensively validated and based on the results the advance multi-node Fiala thermoregulation model was chosen as a basis for UTCI. The UTCI temperature for a given combination of meteorological variables is defined as the air temperature in the reference condition of humidity, radiation and wind speed, which produces the same strain index value as in actual conditions. As this dynamic physiological response is multidimensional, a single dimensional strain index is calculated based on principal component analysis. The associated assessment scale ranges from extreme cold stress through neutral to extreme heat stress. For the calculations of UTCI the polynomial regression equation was found.

A wide range of potential applications was identified. The most prominent can be applications in the field of public weather services (weather reports, warnings etc), public health systems, urban planning, tourism and recreation and climate impact research. An example presents only one of the possible UTCI application.

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