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Comparison of UTCI to selected thermal indices

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Abstract Over the past century more than 100 indices have been developed and used to assess bioclimatic conditions for human beings. The majority of these indices are used sporadically or for specific purposes. Some are based on generalized results of measurements (wind chill, cooling power, wet bulb temperature) and some on the empirically observed reactions of the human body to thermal stress (physiological strain, effective temperature). Those indices that are based on human heat balance considerations are referred to as "rational indices". Several simple human heat balance models are known and are used in research and practice. This paper presents a comparative analysis of the newly developed Universal Thermal Climate Index (UTCI), and some of the more prevalent thermal indices. The analysis is based on three groups of data: global data-set, synoptic datasets from Europe, and local scale data from special measurement campaigns of COST Action 730. We found the present indices to express bioclimatic conditions reasonably only under specific meteorological situations, while the UTCI represents specific climates, weather, and locations much better. Furthermore, similar to the human body, the UTCI is very sensitive to changes in ambient stimuli: temperature, solar radiation, wind and humidity. UTCI depicts temporal variability of thermal conditions better than other indices. The UTCI scale is able to express even slight differences in the intensity of meteorological stimuli.

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Introduction

Throughout the last century there has been much active research on how to define thermal comfort and how to grade thermal stress. These efforts have resulted in various models attempting to describe thermal comfort and the resultant thermal stress. A large number of indices have been proposed, which are (or were) in use throughout the world [about 40 indices were listed by Epstein and Moran (2006) and there are many others].

Thermal stress indices can be divided into three groups according to their rationale (Parsons 2003; NIOSH 1986): (1) indices based on calculations involving the heat balance equation ("rational indices"), e.g.,

the heat stress index (HSI) for warm weather (Belding and Hatch 1955) or the required clothing insulations (IREQ; Holmér 1984) for cold environments; (2) indices based on objective and subjective strain ("empirical indices"), e.g., the physiological strain index (PSI; Moran et al. 1998); and (3) indices based on direct measurements of environmental variables ("direct indices"); e.g., the apparent temperature (AT) (Steadman 1984), the operative temperature (Blazejczyk et al. 1998) and the wet-bulb globe temperature (WBGT) (Yaglou and Minard 1957). Obviously, indices of the first two groups are more difficult to implement for daily use, since they depend on many variables and some of them require invasive measurements. The third group of indices, based on monitoring of environmental variables, is more user-friendly and applicable.

In 1916, Hill introduced the kata-thermometer, in which both dry and wet temperature readings are taken. Wind-tunnel experiments formed the empirical basis for constructing predictive formulas of so-called "cooling power" to describe the rate of heat loss. Accordingly, the cooling rate of the wet kata is dependent on wind speed and ambient humidity while heat loss of the dry kata depends on wind speed and ambient temperature (Hill et al. 1916). The physical principle of the dry kata-thermometer served also Siple and Passel (1945), who introduced the wind chill index (WCI), which represents dry heat loss from human skin when exposed to a rather cold environment (lower than 10°C).

Houghton and Yaglou (1923) proposed the effective temperature (ET) index. This index was established to provide a method for determining the relative effects of air temperature and humidity on comfort. Originally, this index covered the temperature range from 1°C to 45°C but, in reality, it was used to assess the level of heat stress. Vernon and Warner (1932) substituted the dry-bulb temperature with a black-globe temperature to allow radiation to be taken into account (the "corrected effective temperature" CET). Since then, many modifications to this basic index were implemented, all of which were aimed to grade heat stress.

Without claiming completeness, a set of available and operationally applied thermal assessment procedures are reviewed below (see also: Driscoll 1992; Fanger 1970; Landsberg 1972; Parsons 2003). These indices are presently being utilized by various national and local weather services around the world, and can be evaluated easily by potential users based on the need to describe heat load and thermoregulatory processes.

The aim of the present paper is to compare the newly developed index—the Universal Thermal Climate Index (UTCI)—with some selected existing procedures. The comparative analysis is based on three groups of data: a global meteorological dataset, a synoptic dataset from Freiburg (Germany) and local scale data from special measurement campaigns of COST Action 730. The special campaigns were carried out in various climates: arctic, subtropical dry, subtropical wet and urban.

Essentials of existing indices

Simple indices

The first group of indices used in this comparative study illustrates the combined effect on the human organism of several, individual meteorological variables: air temperature, wind speed, and air humidity. Some of these indices are based on empirical research (e.g., ET, WCI), and some on theoretical considerations. This paper considers only those indices that provide temperature as an output value.

Heat index

The heat index (HI) is an index that combines air temperature and relative humidity to determine an apparent temperature—how hot it actually feels. The HI equation (Rothfusz 1990) is derived by multiple regression analysis in temperature and relative humidity from the first version of Steadman's (1979) apparent temperature (AT). When humidity is high, the evaporation rate of water is reduced (although relative humidity is used in the formula, the term "relative" is misleading in the context of the statement). This means heat is removed from the body at a lower rate, causing it to retain more

Table 1 Assessment scale of heat index (HI)[a]

Heat Index (°C)	Category	Possible heat disorders for people in high risk groups
27–32	Caution	Fatigue possible with prolonged exposure and/or physical activity
32–41	Extreme caution	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity
41–54	Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity
≥ 54	Extreme danger	Heat stroke or sunstroke likely

[a] Source: http://www.crh.noaa.gov (24 January 2011)

heat than it would in dry air. HI, which is widely used in the United States, is calculated as follows:

$$
\begin{aligned}
HI = &-8.784695 + 1.61139411 \cdot T + 2.338549 \cdot RH \\
&-0.14611605 \cdot T \cdot RH - 1.2308094 \cdot 10^{-2} \cdot T^2 \\
&-1.6424828 \cdot 10^{-2} \cdot RH^2 + 2.211732 \cdot 10^{-3} \cdot T^2 \cdot RH \\
&+7.2546 \cdot 10^{-4} \cdot T \cdot RH^2 - 3.582 \cdot 10^{-6} \cdot T^2 \cdot RH^2
\end{aligned}
\tag{1}
$$

where: T is air temperature in °C, and RH is relative humidity rounded to its integer value in %.

HI is valid for air temperatures above 20°C and its values are categorized due to possible heat disorders in people (Table 1):

Humidex

The Humidex is a Canadian innovation, first used in 1965 and revised by Masterson and Richardson (1979). It was devised by Canadian meteorologists to describe how hot, humid weather is felt by the average person. The Humidex is in use in weather forecast routine in Canada. It combines air temperature (T, in °C) and air vapor pressure (vp, in hPa) into one number to reflect the perceived temperature.

$$
Humidex = T + 0.5555 \cdot (vp - 10)
\tag{2}
$$

where:

$$
vp = 6.11 \cdot e^{\left(5417.753 \cdot \left(\frac{1}{273.16} \right) \cdot \left(\frac{1}{(273.16 + td)} \right) \right)}
\tag{3}
$$

and td is dew point temperature (in °C).

The assessment scale of Humidex provides information regarded danger category and possible heat syndrome (Table 2).

Effective temperature

The term "effective temperature" was first used within the community of occupational physiologists. Houghton and Yaglou (1923) introduced the effective temperature index

Table 2 Assessment scale of Humidex: degree of comfort[a]

Humidex (°C)	Degree of comfort
20–29	No discomfort
30–39	Some discomfort
40–45	Great discomfort; avoid exertion
46 and over	Dangerous; possible heat stroke

[a] Source: http://www.ec.gc.ca/meteo-weather/ (→ hazardous weather→ summer weather→summer hazards→heat and humidity→humidex, 24 January 2011)

(ET). This index was originally established to provide a method of determining the relative effects of air temperature and humidity on comfort.

Missenard (1933) developed a mathematical formulation of effective temperature ("température résultante"). The index establishes a link between the identical state of the organism's thermoregulatory capacity (warm and cold perception) and differing temperature and humidity of the surrounding environment. Using this index, it is possible to obtain the effective temperature felt by the human organism for certain values of meteorological parameters such as air temperature, relative humidity of air, and wind speed, which determine the thermal exchange between the organism and the environment. By considering normal atmospheric pressure and a normal human body temperature (37°C), consideration of the above mentioned parameters is reflected in the suggested expression. Missenard's ET was used widely in East Germany, Poland, the Soviet Union, etc. The ET is still in use in Germany, where medical check-ups for subjects working in the heat are decided on by prevailing levels of ET, depending on metabolic rates. Li and Chan (2000) have adapted the Missenard formula and named it "Normal Effective Temperature" (NET). The NET is routinely monitored by the Hong Kong Observatory. The original Missenard formula for ET (NET) takes the following form:

$$
ET = 37 - \frac{37 - T}{0.68 - 0.0014 \cdot RH + \frac{1}{1.76 + 1.4 v^{0.75}}} - 0.29 \cdot T \cdot (1 - 0.01 \cdot RH)
\tag{4}
$$

where: v is wind speed (in m s^{-1}) at 1.2 m above the ground.

Several assessment scales are adapted for ET. In central Europe the following thresholds are in use: <1°C = very cold; 1–9 = cold; 9–17 = cool; 17–21 = fresh; 21–23 = comfortable; 23–27 = warm; >27°C = hot. In Poland, Baranowska and Gabryl (1981) developed an ET scale based on 3-year's worth of questionnaire research conducted by meteorological station staff. The scale includes seasonal changes of sensations resulting from the physiological adaptation to weather and clothing habits (Fig. 1). In Hong Kong the weather service uses NET as a warning system. The alert procedure is a little complicated. Based on a 28-year database, the authors calculated NET, analyzing statistical distribution of NET values separately for summer (May–September) and winter (November–March) seasons. They chose a 2.5% limit of extremely high (for summer) and extremely cold (for winter) NET values and used them to define a so-called weather stress index (WSI). In operational use, forecasters refer to special look-up tables that identify
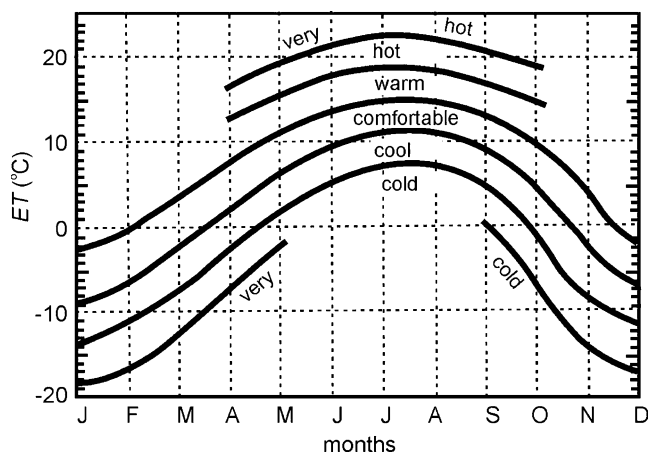
Fig. 1 Effective temperature (ET) thresholds at different months in Poland (after Baranowska and Gabryl 1981)

the possible occurrence of summer and winter WSI based on combinations of temperature, relative humidity and wind speed.

Wet-bulb-globe-temperature

The wet-bulb globe temperature (WBGT) is the heat stress index most widely used by far throughout the world. It was developed by the US Navy as part of a study on heat-related injuries during military training (Yaglou and Minard 1957). The WBGT index, which emerged from the "corrected effective temperature" (CET) (Vernon and Warner 1932) consists of weighting of dry-bulb temperature, natural (un-aspirated) wet-bulb temperature and black-globe temperature. For indoor conditions, when the black-globe temperature equals approximately ambient dry temperature, the index consists of only wet-bulb and black-globe temperatures.

Based on the WBGT index, the American Conference of Government Industrial Hygienists (ACGIH) published the *Permissible heat exposure threshold limits values (TLV)*, which refer to those heat stress conditions under which nearly all workers may be repeatedly exposed without adverse health effects (ACGIH 2004). These criteria were adopted also by the Occupational Safety and Health Administration (OSHA, http://www.

osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html, 16 March 2011) and the American Industrial Hygiene Association (AIHA 1975). The American College of Sports Medicine (ACSM) and the US Army published guidelines for exercising under various levels of heat stress (Armstrong et al. 1996; Department of the Army 1980). Yet, the inherent limitation of the WBGT is its limited applicability across a broad range of potential scenarios and environments, because of the inconvenience of measuring T_g. In many circumstances measuring T_g is cumbersome and impractical (Moran and Pandolf 1999; NIOSH 1986). Due to the limitations mentioned above, the present study was based on a simplified equation of WBGT (http://www.bom.gov.au/info/thermal_stress/, 16 March 2011).

$$WBGT = 0.567 \cdot T + 0.393 \cdot vp + 3.94 \qquad (5)$$

The following ranges of WBGT indicate detailed recommendations for outdoor activity (Table 3).

Apparent temperature

The AT is defined as the temperature at the reference humidity level producing the same amount of discomfort as that experienced under the current ambient temperature, humidity, and solar radiation (Steadman 1984). Basically, the AT is an adjustment to the ambient temperature (T) based on the level of humidity. Absolute humidity with a dew point of 14°C is chosen as a reference. If humidity is higher than the reference, then the AT will be higher than T; if humidity is lower than the reference, then AT will be lower than T. The amount of deviation is controlled by the assumptions of the Steadman model (Steadman 1984). AT is valid over a wide range of temperatures. It includes the chilling effect of the wind at lower temperatures. A simple hot weather version of the AT is known as the heat index (HI, see above).

Two formulas for AT are in use by the Australian Bureau of Meteorology: one includes solar radiation and the other one does not (http://www.bom.gov.au/info/thermal_stress/, 16 March 2011). For the present discussion, the "non-radiation" version was used.

$$AT = T + 0.33 \cdot vp - 0.7 \cdot v - 4.0 \qquad (6)$$

Table 3 Recommendations for outdoor activity at various wet-bulb globe temperature (WBGT) ranges[a]

WBGT (°C)	Recommended sporting activity
< 18	Unlimited
18–23	Keep alert for possible increases in the index and for symptoms of heat stress
23–28	Active exercise for unacclimatized persons should be curtailed
28–30	Active exercise for all but the well-acclimated should be curtailed
> 30	All training should be stopped

[a] Source: http://www.bom.gov.au/info/wbgt/wbgtrecs.shtml, 24 January 2011)

Wind chill

Assessment of the effects of wind in cold environments on exposed skin areas has long been of great interest. Siple and Passel (1945) exposed snow-melted water in a plastic container to combine subfreezing environmental temperatures and wind speeds in the Antarctic. Wind chill index WCI (W m^{-2}) was calculated, expressing the cooling power of the wind in complete shade and without any evaporation, as is suggested in ISO TR 11079 (1993). This enabled development of the wind chill temperature WCT (ASHRAE 1997), which defines an equivalent environment, of which the cooling power is identical to that of the actual, windy environment. The *WCT* was used until recently by the weather services in North America as an essential winter weather predictor. In the present study the WCT was used as follows:

$$WCT = 13.12 + 0.6215 \cdot T - 11.37 \cdot v_{10}^{0.16}$$
$$+ 0.3965 \cdot T \cdot v_{10}^{0.16} \qquad (7)$$

where v_{10} is wind speed (in m s^{-1}) at 10 m above ground level.

The following WCT-related health hazards can be defined (Table 4).

The original experiments by Siple and Passel (1945) were criticized by several investigators who stated that, in cases of WCT, the predicted values were not reliable (Kessler 1993; Molnar 1958; Osczevski 1995a, 2000; Steadman 1971). Alternative wind chill indicators—exposed skin temperature and maximum exposure times—were

proposed by Brauner and Shacham (1995). Several studies that used a steady-state model of facial cooling were conducted by Bluestein (1998), Bluestein and Zecher (1999) as well as by Osczevski (1995b, 2000). Tikuisis and Osczevski (2002, 2003) developed a different model of facial cooling, which was solved numerically to yield imminent freezing times. Tikuisis (2004) introduced a tissue cooling model including the effects of blood flow for the prediction of the onset of finger freezing. By employing a one dimensional, steady-state cylindrical model of the head/face, Shitzer (2006) assessed the convective heat transfer coefficients on wind chill.

In 2001 the National Weather Service in the USA and Environment Canada replaced the "old" WCT charts with a "new" wind chill equivalent temperature WCET (OFCM 2003). Values assessed by this "new" method for combinations of wind and temperature are considerably higher (warmer) than those predicted by the old one. The numerical model was solved iteratively. Wind chill equivalent temperatures were approximated by a mathematical regression equation based on air temperature and reported wind speed, and presented in numerical tables. Estimates of the risk of frostbite under various conditions were added to the charts by Tikuisis and Osczevski (2002). In this model, a target skin temperature of −4.8°C is used for a 5% risk of frostbite. WCET is defined as "the air temperature of an equivalent environment that, under calm wind conditions, would entail the same skin surface heat loss to the environment as in the actual, windy, environment" (Osczevski and Bluestein 2005). For more details about the wind chill problem, see Shitzer and Tikuisis (2011).

Table 4 Characteristics of wind chill temperature (WCT)-related health hazards[a]

WCT (°C)	Risk of frostbite	Health concern
0 to −9	Low	Slight increase in discomfort
-10 to −27	Low	Uncomfortable. Risk of hypothermia if outside for long periods without adequate protection
-28 to −39	Risk: exposed skin can freeze in 10–30 min	Risk of frosnip or frostbite: check face and extremities for numbness or whiteness
		Risk of hypothermia if outside for long periods without adequate clothing or shelter from wind and cold
-40 to −47	High risk: exposed skin can freeze in 5–10 min[b]	High risk of frostbite: check face and extremities for numbness or whiteness
		Risk of hypothermia if outside for long periods without adequate clothing or shelter from wind and cold
-48 to −54	Very high risk: exposed skin can freeze in 2–5 min[b]	Very high risk of frostbite: Check face and extremities frequently for numbness or whiteness
		Serious risk of hypothermia if outside for long periods without adequate clothing or shelter from wind and cold
-55 and colder	Extremely high risk: exposed skin can freeze in less than 2 min[b]	DANGER! Outdoor conditions are hazardous

[a] Source: http://www.ec.gc.ca/meteo-weather/ (→ hazardous weather → winter weather → winter hazards → wind chill → wind chill index, 24 January 2011)

[b] In sustained winds over 50 km/h, frostbite can occur faster than indicated

Indices derived from heat budget models

Heat budget models of the human body take all mechanisms of heat exchange into account. Some models, such as the required clothing insulation (IREQ; ISO TR 11079, 1993) or the predicted heat strain (PHS; ISO 7933 2004) provide sets of output indices rather than one specific temperature value. These indices are used as physiological standards to assess occupational environment in the cold or in the heat. In the present paper, selected indices derived from different heat budget models were compared with the UTCI.

Standard effective temperature

The (rational) standard effective temperature, SET*, is defined as the equivalent air temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature T_{sk}) and thermoregulatory strain (skin wettedness, w) as in the actual environment. SET* uses skin temperature and skin wettedness as the limiting conditions. The values for T_{sk} and w are derived from a two-node model of human physiology (Gagge et al. 1971, 1986). Below the lower threshold value of w, SET* is identical with the operative temperature, i.e., the mean of convective and radiative sensible fluxes weighted by their respective heat transfer coefficients. For outdoor application, SET* has been adapted to OUT_SET* (Pickup and de Dear 2000). For SET* calculations, this paper uses a metabolic rate set at 1.5 MET (about 90 W m^{-2}) and intrinsic clothing insulation of 0.50 clo. Because SET* aims originally at an improved evaluation of warm / humid conditions, the lowest threshold value of the assessment scale (Table 5) is set at +17°C for cool conditions.

Predicted mean vote

Assuming that the sensation experienced by a person is a function of the physiological strain imposed by the environment, Fanger (1970) predicted the actual thermal sensation as the mean vote (PMV) of a large group of persons on the ASHRAE (1997) 7-point scale of thermal sensation. This he defined as "the difference between the internal heat production and the heat loss to the actual environment for a person kept at the comfort values for skin temperature and sweat production at the actual activity level". Fanger calculated this extra load for people engaged in climate chamber experiments and plotted their comfort vote against it. Accordingly, Fanger was able to predict the comfort vote that would arise from a given set of environmental conditions for a given clothing insulation and metabolic rate. The final equation for optimal thermal comfort is fairly complex. However, ISO Standard 7730 (2005) includes a computer programme for calculating PMV.

Physiological equivalent temperature

The physiological equivalent temperature (°C) is based on a complete heat budget model of the human body (Höppe 1984, 1999). PET provides the equivalent temperature of a isothermal reference environment with a water vapor pressure of 12 hPa (50% at 20°C) and light air (0.1 m s^{-1}), at which the heat balance of a reference person is maintained with core and skin temperature equal to those under the conditions being assessed. For the reference person, a typical indoor setting is selected with work metabolism of 80 W added to basic metabolism and with clothing insulation of 0.9 clo. The influence of humidity on PET is restricted to latent heat fluxes via respiration and via diffusion through the skin. The PET assessment scale (see Table 5) is derived

Table 5 Temperature thresholds (°C) of particular thermal sensations (of alert descriptions) used in various bioclimatic indices

Thermal sensation	Index								
	HI	Humidex	ET	WBGT	WCT	SET*	PET	PT	PST
Frosty (extreme hazard)[a]					< −55			< −39	< −36
Very cold (very cold ¹)[a]			< 1		-54 to −40	< 4		−39 − −26	−36 − −16
Cold (cold)[a]			1−9		−39 tp −28		4−8	−26 − −13	−16−4
Cool (moderate hazard)[a]			9−17		−27 to −10	<17	8−18	−13−0	4−14
Comfortable (no danger)[a], [a]		<30	17−21	<18	>−10	17−30	18−23	0−20	14−24
Warm (caution)[b]	27−32	30−40	21−23	18−24		30−34	23−35	20−26	24−34
Hot (extreme caution)[b]	32−41	40−45	23−27	24−28		34−37	35−41	26−32	34−44
Very hot (danger)[b]	41−54	45−55	>27	28−30		>37	>41	32−38	44−54
Sweltering (extreme danger)[b]	>54	>55		>30				>38	>54

[a] Alert descriptions for WCT

[b] Alert descriptions for HI, Humidex and WBGT

by calculating Fanger's (1970) PMV for varying air temperatures in the reference environment using the settings for the PET reference person (Matzarakis et al. 1999). Hence, PET is comfort based.

Perceived temperature

Fanger's (1970) PMV-equation, including Gagge's improvement of the description of latent heat fluxes (Gagge et al. 1986), is the basis for the operational thermal assessment procedure entitled the Klima-Michel-model (Jendritzky 1990; Jendritzky et al. 1979). This is used by the German Meteorological Service (Deutsche Wetterdienst, DWD). The output parameter is perceived temperature (PT; °C) (VDI 2008; Staiger et al. 2011), because an equivalent temperature makes the evaluation of thermal perception to the public more comprehensible than PMV. PT is defined as the equivalent temperature of an isothermal reference environment with a wind reduced to light air and a relative humidity of 50%, where the same perception of warm or cold assessed by PMV would occur as under the actual environment. The reference person has a metabolic rate of 135 (W m^{-2}) and the clothing insulation can be varied between 0.5 clo (warm / summer) and 1.75 clo (cold / winter) to achieve as much thermal comfort as possible. Hence, PT is related to outdoor conditions. Due to the PMV base, its assessment scale (Table 5) is comfort based. The implemented enthalpy correction (Gagge et al. 1986) increases the humidity sensitivity of PT under warm conditions markedly compared to Fanger's original PMV.

At the DWD, this procedure runs operationally taking acclimation quantitatively by a procedure termed HeRATE (health related assessment of the thermal environment) (Koppe and Jendritzky 2005). This procedure has the advantage of using the index without modification in different climate regions and at different times of the year without the need to artificially define seasons and to calibrate them to a particular city. Nevertheless, to date, DWD is the only national weather service to run a complete heat budget model (Klima-Michel-model) on a routine basis specifically for applications in human biometeorology.

Physiological subjective temperature and physiological strain

The PST and PhS indices are derived from the man-environment heat exchange (MENEX) model first published in 1994 (Blazejczyk 1994). This model considers heat exchange between the whole human body and its surroundings. Upon the last modifications of the model (Blazejczyk 2005, 2007; Blazejczyk and Matzarakis 2007), the MENEX_2005 provides output data information on particular heat fluxes as well as several thermo-physiological indices: physiological strain (PhS), physiological subjective temperature (PST), water loss (SW), overheating risk (OhR) and overcooling risk (OcR).

Physiological subjective temperature (PST) represents the subjective sensation by persons of the thermal environment that is derived from signals of cold and/or warm receptors in the skin and in the nervous system. Thermal impacts of the environment are expressed through mean radiant temperature formed under clothing (innerTmrt). PST is defined as the temperature that is formed around the skin surface, under clothing, after a 15–20 min of adaptation to maintain homeothermy. PST indicates an effect of environmental factors and of specific physiological responses to thermal stimuli. PST can be used in a wide range of environmental conditions. The index is limited to wind speeds lower than 22 m s^{-1}.

Physiological strain (PhS) indicates the direction and intensity of predominant adaptation processes to cold or warm environments. PhS is based on the Bowen Ratio and is expressed as the ratio between evaporative and convective heat fluxes.

A set of indices derived from the MENEX_2005 model are in operational use by the National and in Military Weather Services for biometeorological forecasting in Poland. They are also used in several other applications, e.g., in epidemiology, urban climatology, climate therapy and tourism research as well as for bioclimatic mapping (Blazejczyk 2002).

Universal thermal climate index

The Universal Thermal Climate Index (UTCI) is expressed as an equivalent ambient temperature (°C) of a reference environment providing the same physiological response of a reference person as the actual environment (for more details see the further articles of this issue, e.g., Weihs et al. 2011). The calculation of the physiological response to the meteorological input is based on a multi-node model of human thermoregulation (Fiala et al. 2001), which is augmented with a clothing model. The passive system of the multi-node model consists of 12 body elements comprising 187 tissue nodes in total. The active system predicts the thermoregulatory reactions of the central nervous system. Static clothing insulation is adjusted to the ambient temperature considering seasonal clothing adaptation habits of Europeans, which notably affects human perception of the outdoor climate. Clothing insulation, vapor resistance and the insulation of surface air layers, are influenced heavily by changing wind speed and body movement and will therefore also influence physiological responses. Thus, the resultant total insulation of the clothing is the static insulation modified by walking speed and the wind speed in the actual environment to which the person is exposed. Similar

considerations were applied for the evaporative resistance of clothing. The non-meteorological reference conditions are set at a metabolic rate of 135 W m^{-2} and a walking speed of 1.1 m s^{-1}. In the meteorological reference, the mean radiant temperature equals the ambient temperature and the wind speed observed 10 m above ground is 0.5 m s^{-1}. The reference humidity is set at 50% for ambient temperatures of the reference≤29°C and at 20 hPa above.

The assessment scale is based on different combinations of rectal and skin temperatures, sweat rate, shivering, etc. that might indicate "identical" strain causing non-unique values for single variables like rectal or mean skin temperature in different climatic conditions with the same value of UTCI. However, due to the high correlation of the single variables with the calculated one-dimensional integrated characteristic value of thermal strain, this variation was limited. Furthermore, the median response to UTCI was in good agreement with the values obtained for reference conditions (for more details, see other articles in this issue). Hence, the assessment scale relates to a temperature-based physiological strain.

Overview of the indices

The selected simple and the more complex heat balance based indices highlight the stages involved in understanding the relationships between thermal environment and human thermal perception. To summarize, the characterization of 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. The simple indices can never fulfil the essential requirement that, for each index-value, there must always be a corresponding meaningful thermo-physiological state (strain intensity), regardless of the combination of the meteorological input values. Thus, their use is limited, results are often not comparable and additional features such as safety thresholds, etc. have to be defined arbitrarily. The difficulties in the comparative use of the various indices are illustrated in Table 5. Particular indices provide different temperature thresholds with the same meaning of thermal sensations or alert descriptions, respectively.

Data and methods

To compare UTCI to selected bioclimatic indices, different datasets of meteorological variables were used. The data were based on various sources: the control run (1971–1980) of the General Circulation Model ECHAM 4 has a resolution of about 1.1° (Stendel and Roeckner 1998). The data consisted of about 65,500 random samples that represent wide range and combinations of meteorological

variables. Air temperature (T) varied from −74.6°C to 47.4°C, air vapor pressure (vp) from 0 hPa to 40.2 hPa, wind speed (v_{10}) from 0.5 m s^{-1} to 30 m s^{-1}. Mean radiant temperature (Tmrt) changed from −92.3°C to 78.7°C. The difference between Tmrt and T was within the range of −18.0°C to 54.0°C.

The second data set used in these studies are synoptic data from Freiburg from the period September 1966–August 1985. The data provided all meteorological parameters used to calculate UTCI and bioclimatic indices. Freiburg is located in the upper Rhine valley in Southwest-Germany. It shows a moderate transient climate dominated by maritime rather than continental air masses.

The third temporal level of comparisons refers to microclimatic data. For the present paper, measurement campaigns were carried out within the frame of COST Action 730 at different locations:

– Svalbard archipelago (in March 2008)—arctic climate,
– Negev Desert (in September 2008)—dry subtropical climate,
– Madagascar Island (in August 2007)—wet subtropical climate,
– Warsaw, Poland (in October 2007)—downtown city in a moderate, transient climate.

The following simple bioclimatic indices were compared with UTCI: Heat index (HI), Humidex, Wet Bulb Globe Temperature (WBGT), Wind Chill Temperature (WCT), Effective Temperature (ET, NET). We also analyzed relationships between UTCI and indices derived from heat budget models: Standard Effective Temperature (SET*), Physiological Equivalent Temperature (PET), Perceived Temperature (PT), Physiological Subjective Temperature (PST). Two non-thermal indices were also used for comparative analysis: Predicted Mean Vote (PMV) and Physiological Strain (PhS).

UTCI and some indices (HI, AT, Humidex, WBGT, WCT, ET, PST and PhS) were calculated using the BioKlima 2.6 software package. PET, PMV and SET* were calculated by Rayman software and PT by the special PT module. The STATGRAPHICS 2.1 software package was used for statistical analysis of compared indices.

Results and discussion

Regression analysis of UTCI vs other bioclimatic indices—global data

The comparison between UTCI and simple meteorological parameters—air temperature (T), mean radiant temperature (Tmrt) and dew point temperature (Td)—

shows that only air temperature is relatively well correlated with UTCI. Nevertheless, the slope coefficient of regression line is only 0.702. This indicates that UTCI and T change at different rates in various ranges of ambient conditions. In general, air temperature below zero is significantly higher than UTCI. Weaker statistic characteristics were found for Tmrt and Td. R^2 coefficients are significant (78.76 and 84.66, respectively). However, the slope coefficients are very low, especially for dew point temperature (Table 6).

For simple indices addressing hot conditions (HI, WBGT, Humidex), correlation with UTCI is very weak. R^2 coefficients are below 50%. The regression lines also differ significantly from the lines of identity. The slope coefficients are very low (0.38–0.63). Weak similarity of simple, hot indices with UTCI results from their philosophy; they combine, in a very simple way, only two meteorological variables, i.e., air temperature and humidity. None of them include solar radiation and wind speed. A significantly better fit was found for two simple indices, AT and ET, that can be applied under a wide range of thermal conditions. The values most similar to those of UTCI were found for indices derived from human heat balance models, i.e., PET, PT and SET*. These three indices take similar approach to UTCI, i.e., they indicate equivalent temperature. The differences in specific values result from the various structures of heat balance models and different

definitions of reference conditions (see above). The final thermal index compared, PST, does not represent equivalent temperature. It indicates the temperature of the thin air layer under clothing, in the neighborhood of temperature receptors in the skin. Because of this assumption, relationships between PST and UTCI is better expressed by a polynomial function than by a linear function (Table 6).

For non thermal indices (PMV, PhS) the relations with UTCI can be described by determination coefficients only. Because of their various units, slope coefficients cannot be analyzed. However, R^2 coefficients show good relationships between the compared indices. In this case, the PhS polynomial function better expresses the relationship with UTCI than the linear function.

Figures 2, 3, 4, 5 illustrate the general conformity between UTCI and other thermal indices. The global data used for comparison represent a very wide range of meteorological variables. The aim of the analysis is to see how similar the existing indices are in comparison to newly developed UTCI. Figure 2 shows the statistical relationships between UTCI and the simple bioclimatic indices used in hot environments (HI, WBGT, Humidex). It is obvious that hot environment indices are rather weakly correlated with UTCI. R^2 are very low, at about 40% for HI and 42–47% for WBGT and Humidex. The slope coefficients vary from 0.38 for WBGT to 0.63 for Humidex (Table 6). The regression lines of the "heat" indices are far from the lines of identity (Fig. 3).

For the wind chill temperature (WCT), the general statistics are markedly higher than for "hot" indices. R^2 is almost 90% and the slope coefficient is 0.81. The regression line is relatively close to the line of identity (Fig. 3, Table 6).

Effective temperature (ET) and apparent temperature (AT) are indices that can be calculated for a wide range of ambient conditions, in spite of the fact that assessment scales represent only their positive values. When comparing ET and AT with UTCI we found significant conformity of their values. For ET, R^2 is 96.97 and for AT, 95.35. While the correlation coefficients are similar to each other, the slope of the regression line is higher for ET than for AT. For ET, the regression line is very close to the line of identity (Fig. 4, Table 6).

The group of indices based on the human heat balance is very well correlated with UTCI. The best results were obtained for SET* (adapted for outdoor conditions). Both the R^2 coefficient (97.54) and the coefficient of the slope of regression line (a=1.02) were best for this group of indices. This may result from the low clothing insulation in SET*, which coincides with relative low values of UTCI in case of higher wind speeds. High correlation and good slope parameters were also found for the PT. It should be noted that the values of SET* and PST changed gradually due to

Table 6 Statistical characteristics of the relationships between Universal thermal climate index (UTCI) and other indices

Index	Slope	R-squared (%)
HI [a]	0.444	39.72
WBGT [a]	0.381	42.46
Humidex [a]	0.629	47.66
WCT [b]	0.810	89.51
AT	0.716	95.35
ET (NET)	0.947	96.97
PET	0.843	96.42
PT	0.968	96.58
SET*	1.021	97.54
PST	0.559	82.24
PST [c]	-	93.10
PhS	-	94.31
PhS [c]	-	96.05
PMV	-	98.12
T	0.702	93.04
Tmrt	0.864	78.76
Td	0.566	84.66

[a] Calculated for air temperature >20°C

[b] Calculated for air temperature <5°C
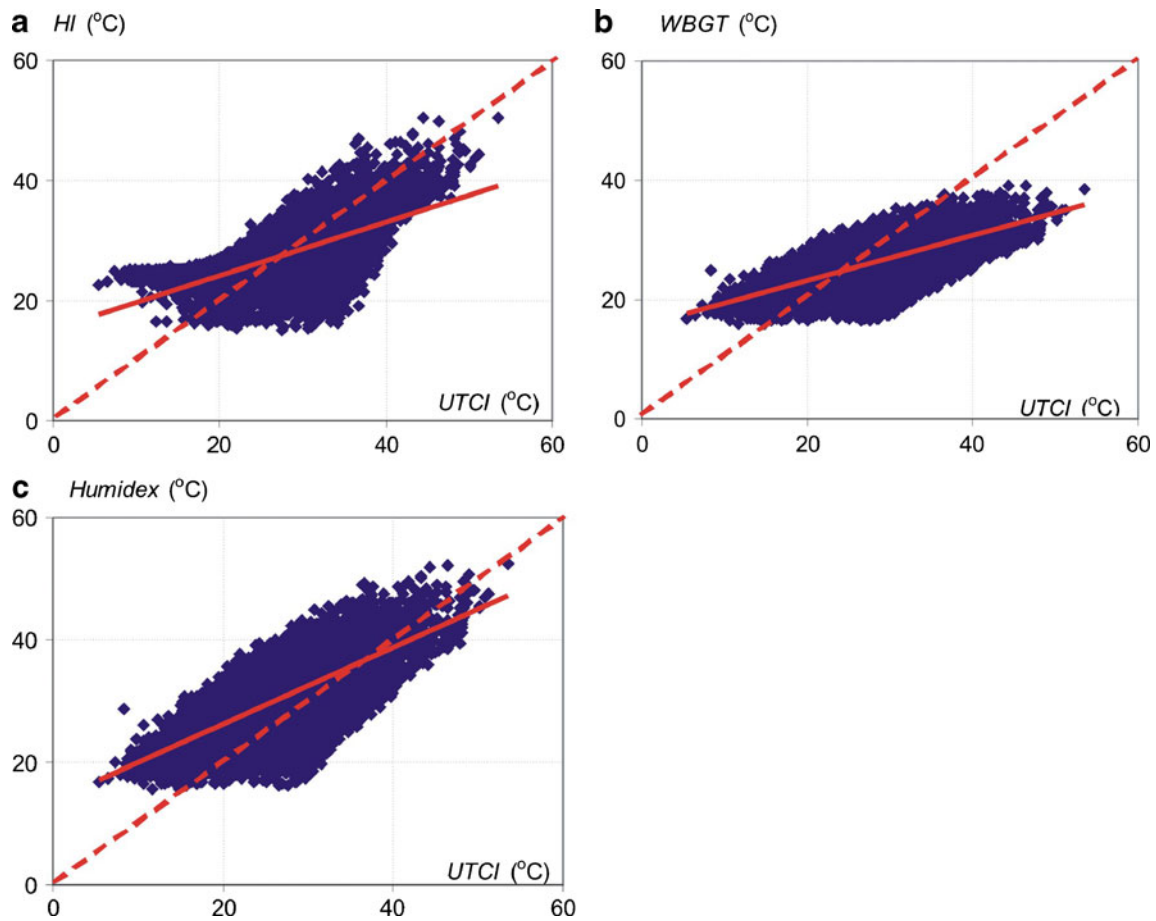
[c] Polynomial function

Fig. 2 Universal thermal climate index (UTCI) vs indices used for hot climates: *HI* heat index, *WBGT* wet bulb globe temperature, Humidex. *Solid line* Regression, *dashed line* identity

the changes of UTCI over the whole temperature range. However, PT and PET have lower limits. PT does not fall below −80°C while UTCI varied from −80 to −110°C. For PET, the lowest value is about −62°C, while UTCI varied
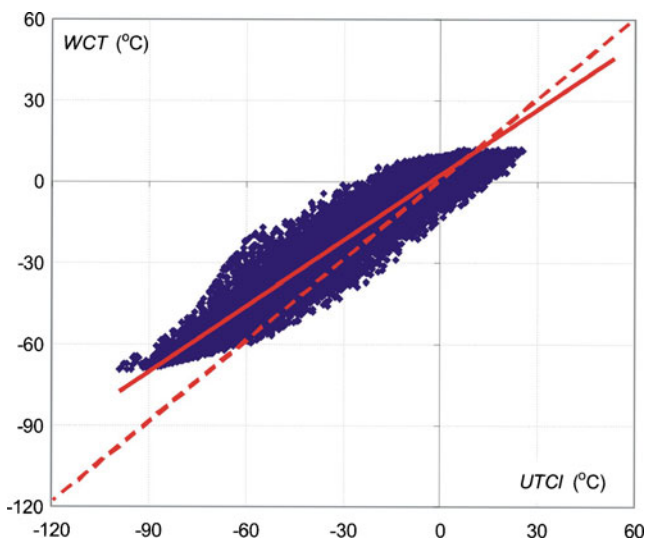

Fig. 3 UTCI vs wind chill temperature (WCT) index. *Solid line* Regression, *dashed line* identity

from −50 to −110°C. The scattering in PT and PET increases with decreasing UTCI, due to their fixed clothing insulation under cold conditions compared with the season and, especially, the wind dependent clothing insulation of UTCI. For the PST index a polynomial function of the 3rd order better expresses its relation with UTCI then linear regression. The R^2 coefficients are 93.10 and 82.24, respectively (Fig. 5, Table 6). In contrast to PT and PET, the scattering in PST increases with increasing UTCI.

The indices PMV and PhS, which are not based on equivalent temperature, also correlate very well with UTCI; $R^2=96.05$ for PhS and $R^2=98.12$ for PMV (Table 6). However, for PhS, a polynomial function of the 3rd order explains the best its relation with UTCI.

The discrepancy between UTCI and the other indices is well seen while comparing the distribution of the residuals (dT=UTCI−any index). In all cases, the range of the residuals is very wide. The weakest agreement is observed with AT. UTCI can be up to −47°C lower and 22°C higher than AT. For AT, the variance was also very high at 95% confidence levels. Relatively narrow dT ranges were found for HI, WBGT and Humidex. However, this is due to the range of applicability of these indices (air temperature >20°C).
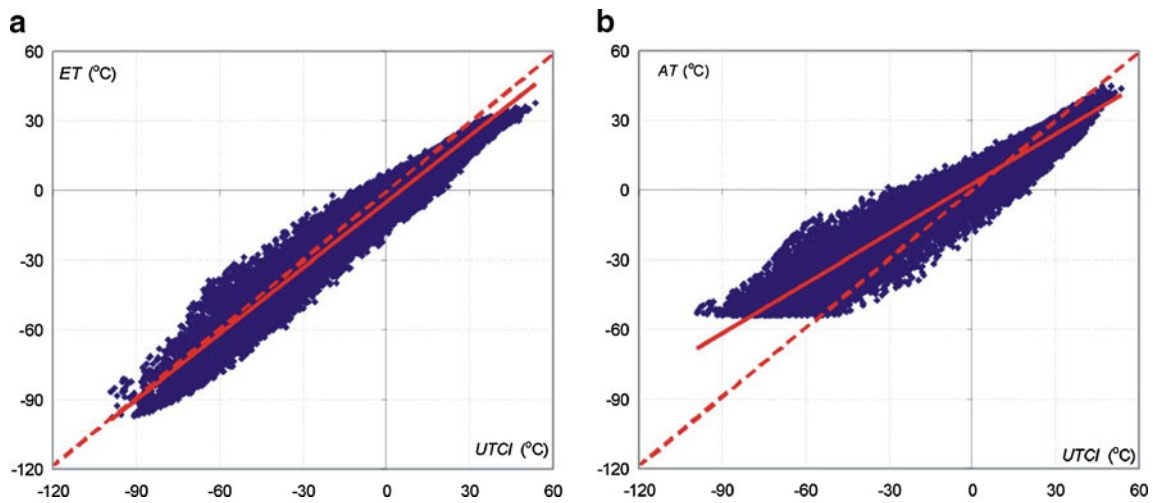
Fig. 4 UTCI vs simple bioclimatic indices. *ET* Effective temperature, *AT* apparent temperature. *Solid line* Regression, *dashed line* identity
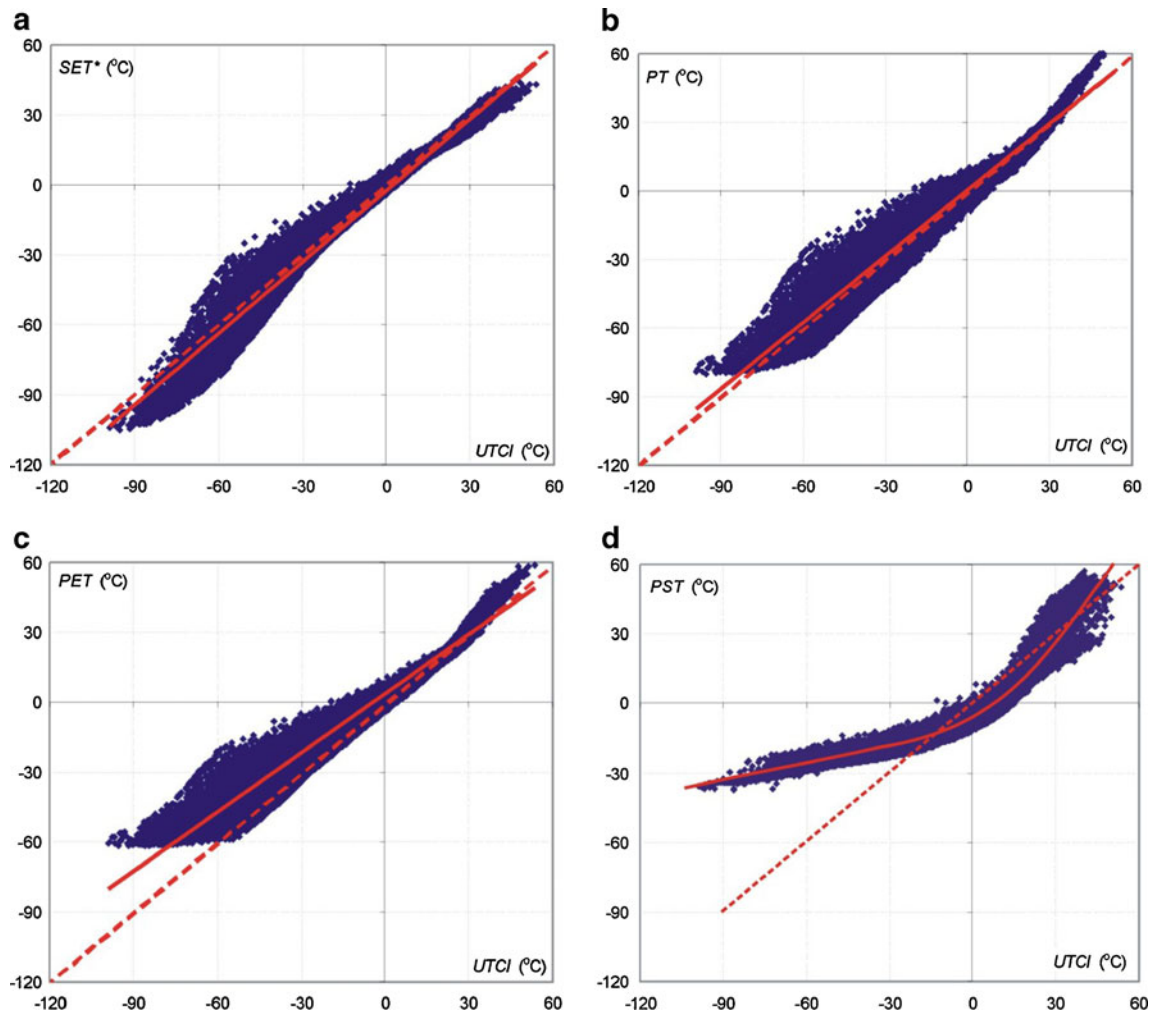

Fig. 5 UTCI vs indices derived from heat budget models. *SET** Standardized effective temperature, *PT* perceived temperature, *PET* physiological equivalent temperature, *PST* physiological subjective temperature. *Solid line* Regression, *dashed line* identity

Table 7 Statistical characteristics of temperature differences between UTCI and other thermal indices	Characteristic	HI	WBGT	Humidex	WCT	AT	ET	PT	PET	SET*
	Max	17.8	17.6	16.9	17.0	21.8	23.0	15.5	5.8	22.8
	Min	-17.8	-27.1	-23.9	-38.4	-47.4	-25.2	-33.6	-39.6	-25.6
	Average (±)	0.4	0.2	-2.8	-8.4	-4.8	4.4	-1.0	-4.8	2.6
		±0.04[a]	±0.06	±0.05	±0.06	±0.07	±0.04	±0.04	±0.04	±0.03
	Variance (±)	30.54	40.36	34.61	67.22	130.29	43.36	37.32	55.73	29.17
[a] ± confidence interval		±0.33	±0.50	±0.43	±0.74	±1.07	±0.36	±0.31	±0.46	±0.24

For ET and SET* the difference range is very symmetrical. They differ from UTCI within the range of −25 to +23°C, with average values of 3–4°C. However, variance points to better conformity of SET* than the ET index. The deviations for PT and PET are very asymmetric. Due to the clothing models differing strongly from UTCI, especially under cold conditions, their values are rather higher than for UTCI. Considering all the statistics of dT, we conclude that the best conformity with UTCI is seen with the SET* and PT indices (Table 7).

UTCI vs other bioclimatic indices—synoptic data

One of the most relevant UTCI applications is weather forecasting based on synoptic data. Staiger (2009, personal communication) reported good correlations ($r=0.89$–0.92) between UTCI and PT for three German stations (Freiburg, Warnemuende and Feldberg) based on data for the period 1966–1995.

In the present study, the concordance of UTCI with previous indices was studied using synoptic data from Freiburg (Germany). For detailed analysis, groups of consecutive days (7–10 and 16–19 January 1982 as well as 12–15 July 1982, representing winter and summer weather, respectively) were selected. Two periods from January were chosen, both with similar air temperature (from −5 to 0°C). The weather from 7–10 January was cloudy (Tmrt from −15 to 10°C) and windy ($v=1$–4 m/s) and from 16–19 January the weather was sunny (Tmrt up to 35°C) and calm ($v<1$ m/s). During cool, cloudy weather, the temporal course of the indices deviated significantly between the simple indices and UTCI (Fig. 6). It seems that UTCI is more sensitive to wind speed than WCT, AT and ET. Comparing UTCI with the heat budget indices, we found that they were well inter-correlated. One exception was the PST index. Its values were significantly lower than for the other indices, especially at weak winds (bottom right panel of Fig. 6). During sunny days, simple indices do not illustrate the impact of solar radiation. However, radiation stimuli are well represented in the heat balance indices: SET*, PT, PET and PST (Fig. 6).

In hot ($T=20$–30°C), windy ($v=2$–8 m/s) and sunny (Tmrt up to 65°C) summer days, simple indices illustrate

well a daily course of bioclimatic conditions. Eminent differences between night and day air temperatures affect these indices. Radiation stimuli, however, are well expressed only in the heat budget indices. In most cases, the values are similar to each other. Only the PST index has considerably lower values during night hours and higher values during daytime hours (Fig. 7).

The general statistics for the Freiburg data illustrate how particular indices differ from air temperature. Two analyses were performed. In the first, the differences between studied bioclimatic indices and air temperature (dT*) were calculated and grouped into 5 K dT* ranges (Table 8). The second analysis compared the frequency of particular classes of indices. In the case of UTCI, its values differed from ambient temperature T within a very wide range, from −46 K to +17 K. However, the majority of dT* values represented the range from −10 to +5 K. In general, UTCI provides values rather lower than air temperature with a noticeable asymmetry of the distribution. For HI, Humidex, AT, PET and PT, the majority of values only slightly differed from T (from −5 to +5 K). This suggests that, for this group of indices, their values depend mostly on ambient temperature. WBGT values are usually higher then T. However, ET, SET* and PST indices provided values lower than air temperature (Table 8).

Analyzing the 20-year database from Freiburg, we compared frequency of particular assessment classes of UTCI with those of other indices (Fig. 8). At this site, UTCI values represent nine classes of the possible ten categories of heat / cold stress, and the other indices eight out of maximal nine categories (Table 5). According to the definition in Table 5, the number of categories is restricted to seven for PET and five for SET* for this study. In Freiburg, extreme cold stress occurred only twice in the studied period. However, extreme heat stress was not observed. The most frequent are synoptic situations varying from moderate cold stress to no thermal stress. Extreme thermal conditions occurred very rarely. A similar range of conditions was also reported by the PST index. However, the proportions between particular classes of thermal sensations different from UTCI; PST indicated a higher frequency of cold conditions than UTCI. ET and PET classes of thermal sensations are moved significantly to

Fig. 6 Temporal course of UTCI compared to the simple (WCT, ET, AT) and the heat budget based (SET*, PT, PET, PST) indices during selected days in January 1982 in Freiburg (Germany)
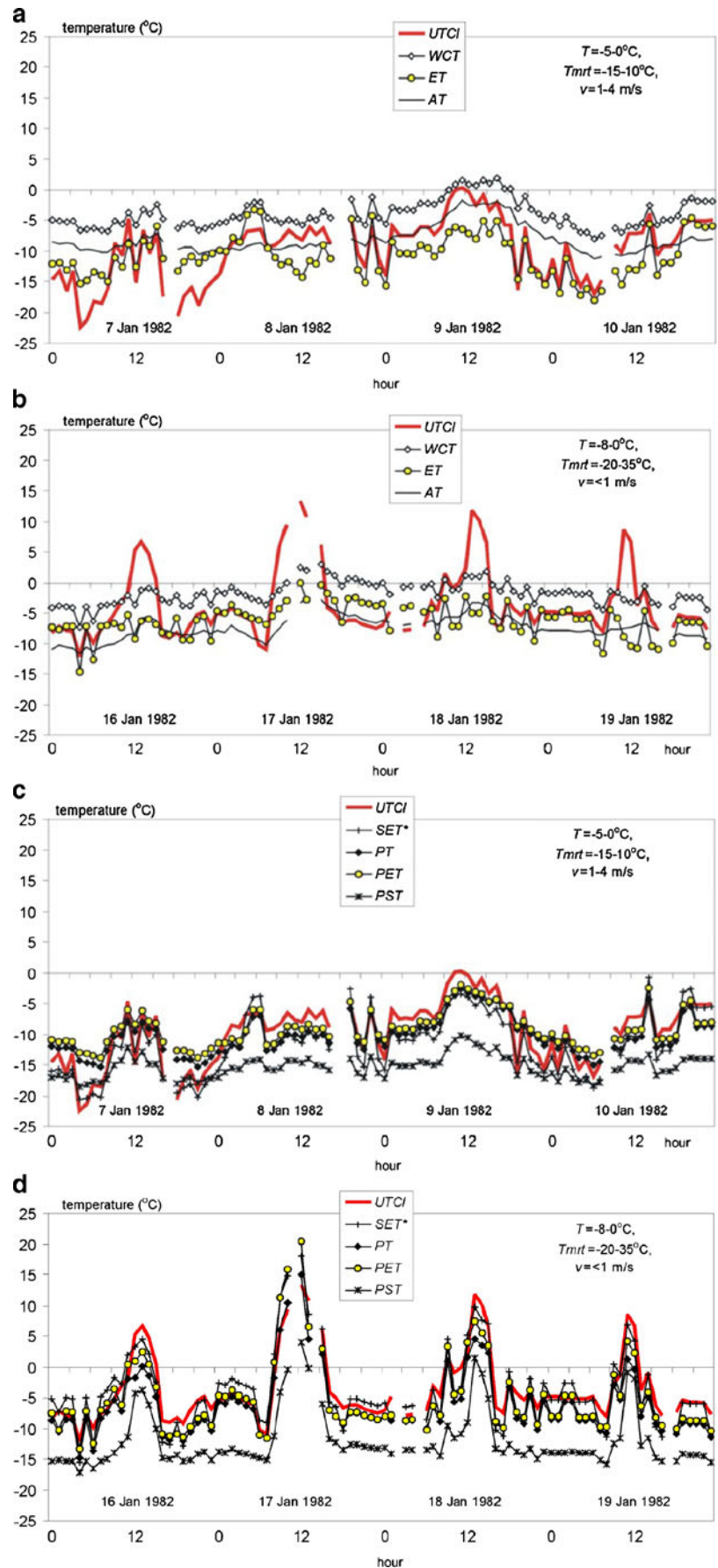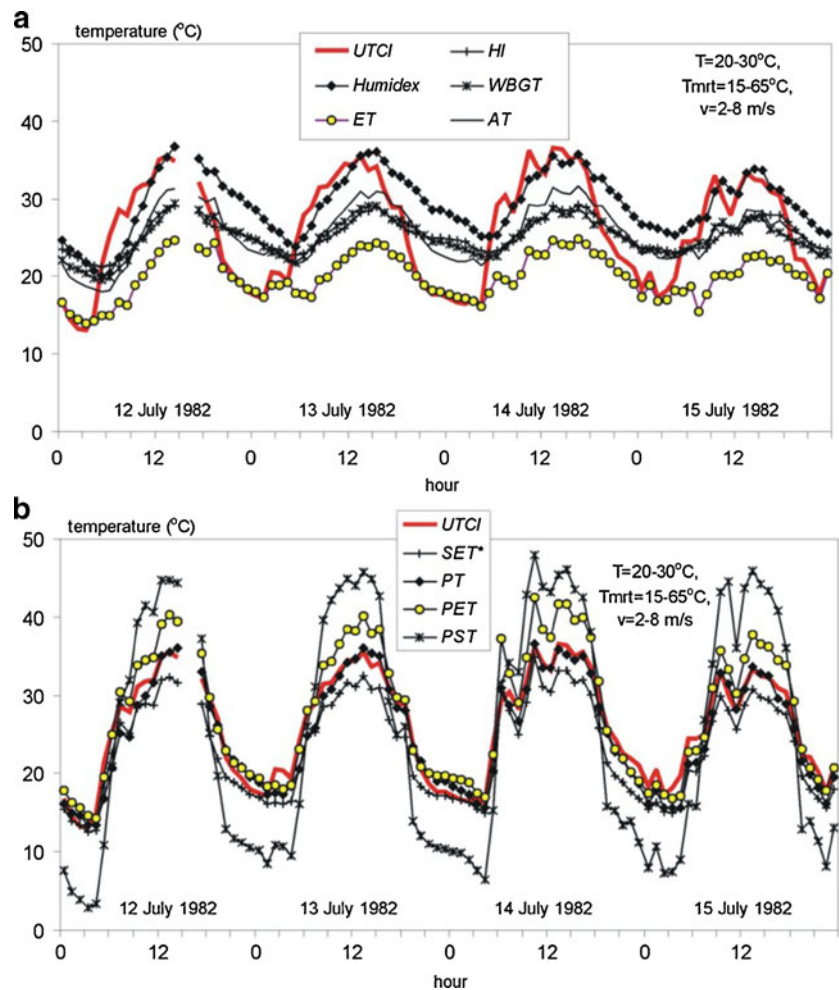
cold and very cold, which, at least for PET, is due to an assessment related to a typical indoor setting concerning clothing insulation and activity. However, PT and SET* indicated milder conditions than UTCI and the other indices (Fig. 8), whereas the lowest SET* category is "cool" (Table 5) and PT is related to a typical outdoor setting for clothing insulation and activity.

In contrast to the strong bias in the assessment scales of the indices (Table 5), there is high correlation between the temperature values of the indices independent from assumptions regarding metabolic rate and clothing insulation. This is not surprising because most of the equivalent temperatures that are related to complete heat budget models, e.g., PT, PET, SET* are derived by solving the heat budget equation for the actual and reference environments for unchanged metabolic rate and clothing insulation. Nevertheless, there are noticeable and significant differences in individual segments of the temperature scale, e.g., between PT and PET under warm conditions, because PT is strongly influenced by skin wettedness. In contrast to e.g., PT, UTCI accounts additionally for a reduction in clothing insulation caused by wind and the movement of the wearer.

Especially in the cold, and in the case of higher wind speeds, the clothing resistance worn in the actual environment can differ strongly from the reference environment with calm air and thus will significantly influence the resulting equivalent temperature.

UTCI vs other bioclimatic indices—microclimatic data

Bioclimatic indices are used widely in various microclimatic applications and specific climates. In the present paper, some examples of microclimatic data were analyzed. On the Svalbard archipelago, measurements were performed on the glacier during a study lasting 12 h, from 7.00 am to 7.00 pm (A. Arazny Preliminary results of biometeorological observations made on Svalbard Archipelago in the winter season 2007/2008. Data file 2009, personal communication)). The 1st and the last 2 h in this dataset represent indoor conditions ($T=15$°C). During outdoor exposure, air temperature fluctuated from −15 to −20°C, wind speed was 8–11 m/s, and the sun was shining only within the hour around noon. The subjects (five young male volunteers) reported strong and very strong cold stress. Among the simple indices, ET had the values

Table 8 Frequency of various ranges of differences bioclimatic index minus air temperature (dT*), Freiburg, 1966–1985. *STD* Standard deviation

dT* range (K)	UTCI	HI	Humidex	WBGT	WCT	ET	AT	SET*	PET	PT	PST
< −45	0.00	.	.	.	.	.	.	.	.	.	.
-45 : -40	.	.	.	.	.	.	.	.	.	.	.
-40 : -35	0.01	.	.	.	.	.	.	.	.	.	.
-35 : -30	0.04	.	.	.	.	.	.	.	.	.	.
-30 : -25	0.33	.	.	.	.	.	.	.	.	.	.
-25 :-20	1.81	.	.	.	.	.	.	.	.	.	.
-20 : -15	5.51	.	0.10	.	.	0.01	.	.	.	.	0.68
-15 : -10	10.15	0.14	4.32	0.57		6.75		0.31	.	.	42.39
-10 : -5	19.15	17.41	32.46	13.85	0.10	75.20	0.04	37.34	.	0.42	40.60
-5 : 0	32.59	29.50	40.59	16.94	33.41	18.04	8.67	31.52	33.42	35.09	9.13
0 : 5	17.71	29.35	21.07	27.21	61.54	0.00	58.80	20.16	61.42	57.18	4.46
5 : 10	10.59	18.71	1.45	24.94	4.95		32.45	8.36	5.10	7.28	2.57
10 : 15	2.10	4.48	.	10.41	.	.	0.04	1.89	0.05	0.01	0.15
15 : 20	0.03	0.42	.	4.66	.	.	0.00	0.34	0.00	0.00	0.01
20 : 25	.	.	.	1.28	.	.	.	0.08	.	0.01	.
25 : 30	.	.	.	0.13	.	.	.	0.00	.	.	.
30 : 35	.	.	.	0.02	.	.	.	.	.	.	.
Min (°C)	-45.9	-12.7	-16.4	-13.6	-7.2	-19.6	-8.0	-14.9	-2.6	-9.2	-17.5
Max (°C)	16.8	19.1	9.0	32.1	8.8	0.7	17.2	25.7	19.6	23.8	16.9
Avg (°C)	-3.5	0.8	-3.3	3.5	1.1	-6.9	3.7	-2.0	1.0	1.0	-8.4
STD (°C)	7.4	5.4	4.1	7.0	2.2	2.1	2.4	5.0	1.8	2.6	4.64

closest to UTCI (Fig. 9). Among the thermo-physiological indices, SET* had the best concordance with UTCI. Additionally, those two indices illustrated very well the changes in bioclimatic conditions due to fluctuations in wind speed (Fig. 9). Similar variations of UTCI in relation to physiological reactions of the organism in polar climates were observed by Blazejczyk et al. (2008) in northern Finland.

Dry subtropical climate was represented by measurements made on the 9 September 2008 in the Negev Desert, in southern Israel. Data collection lasted about

3.5 h and had two phases: travelling in an air-conditioned bus (air temperature about 25–27°C) and walking in the desert (at temperature of 35–40°C, humidity of 15–25% and weak wind <2 m/s). During outdoor exposure ,microclimatic conditions were felt by subjects (four male and two females) as high and very high heat stress. The changes in bioclimatic conditions due to changes in exposure (indoor–outdoor) were indicated very well by all the heat stress measures compared here. However, the values obtained for

Fig. 8 Frequency of particular assessment classes of UTCI (*left panel*) and classes of thermal sensations defined by other indices, Freiburg, Germany, September 1966–August 1985
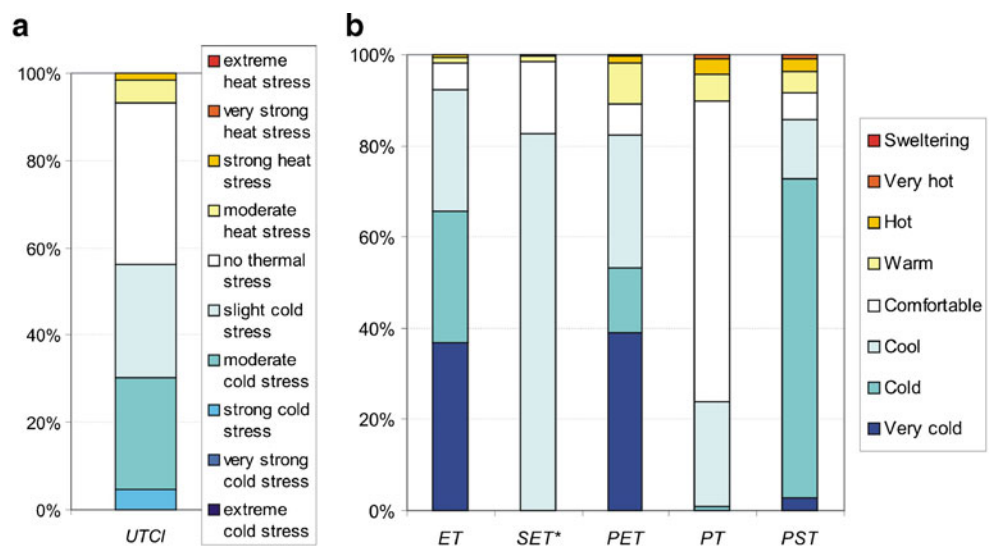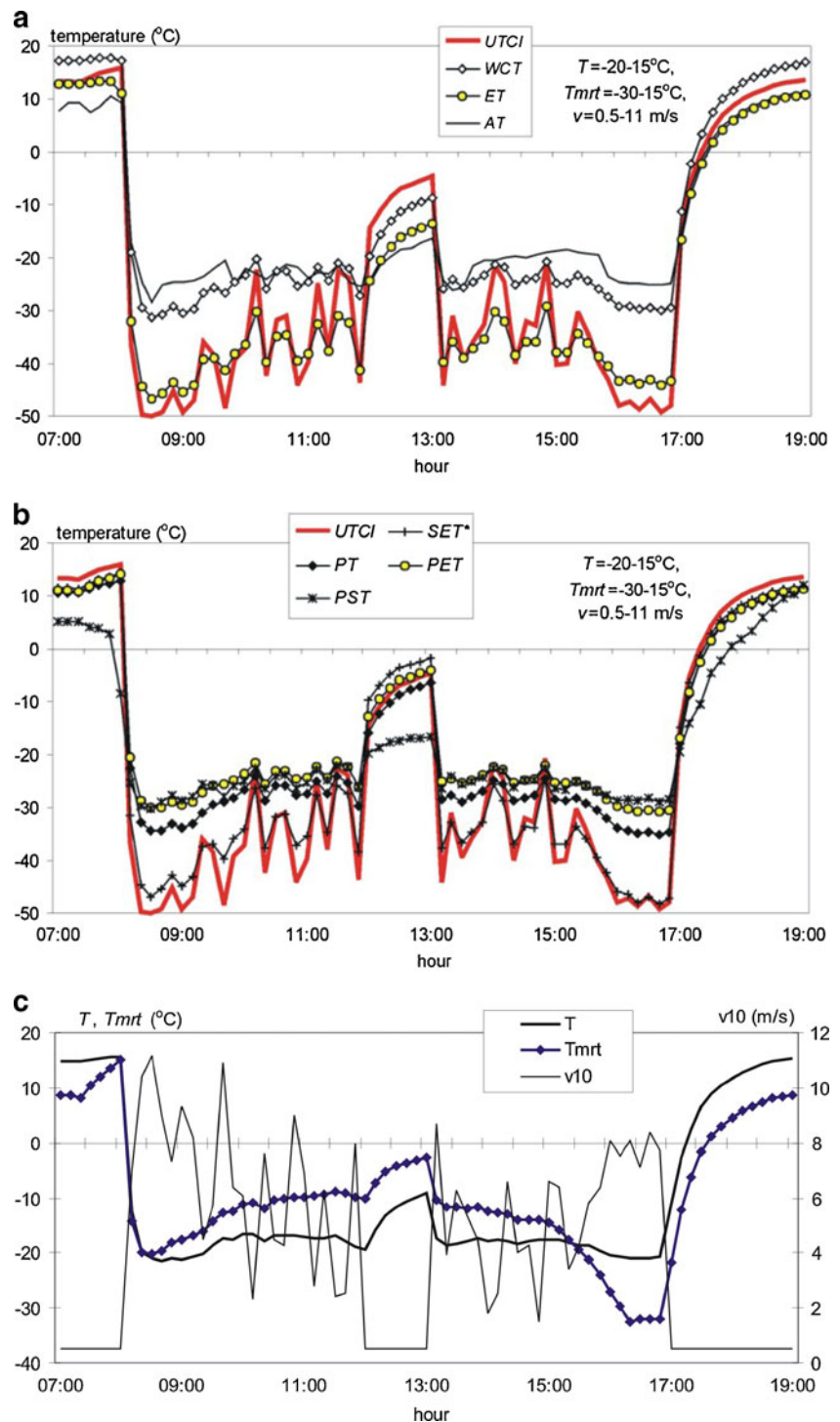
Fig. 9 Changes of UTCI and other bioclimatic indices during a 12-h experiment on Svalbard archipelago in arctic climate on 23 March 2008; *lower panel* course of meteorological variables (*T*, Tmrt, v10)


particular indices were very different from one another. Usually PET values were higher and ET and WBGT lower than UTCI (Fig. 10).

In a wet subtropical climate in the central part of the Island of Madagascar, bioclimatic conditions were controlled during a 6.5-h exposure on 22 August 2007. In the morning, the air temperature was 20°C and during midday it rose to about 33°C. Air humidity was very high during the whole data collecting period (70–80%). The weather was sunny with moderate wind. Subjects (five males and one female) reported thermo-neutral conditions in the morning and high to very high heat stress during the midday hours. The closest to UTCI values (Fig. 11) were found for AT, WBGT and PET indices. ET, SET* and PST values were consequently lower then UTCI. However, HI, Humidex and PT provided values significantly higher then

Fig. 10 Changes of UTCI and other bioclimatic indices during 3.5 h of observation in the Negev Desert in a dry subtropical climate, 9 September 2008; *lower panel* course of meteorological variables (*T*, Tmrt, v10)
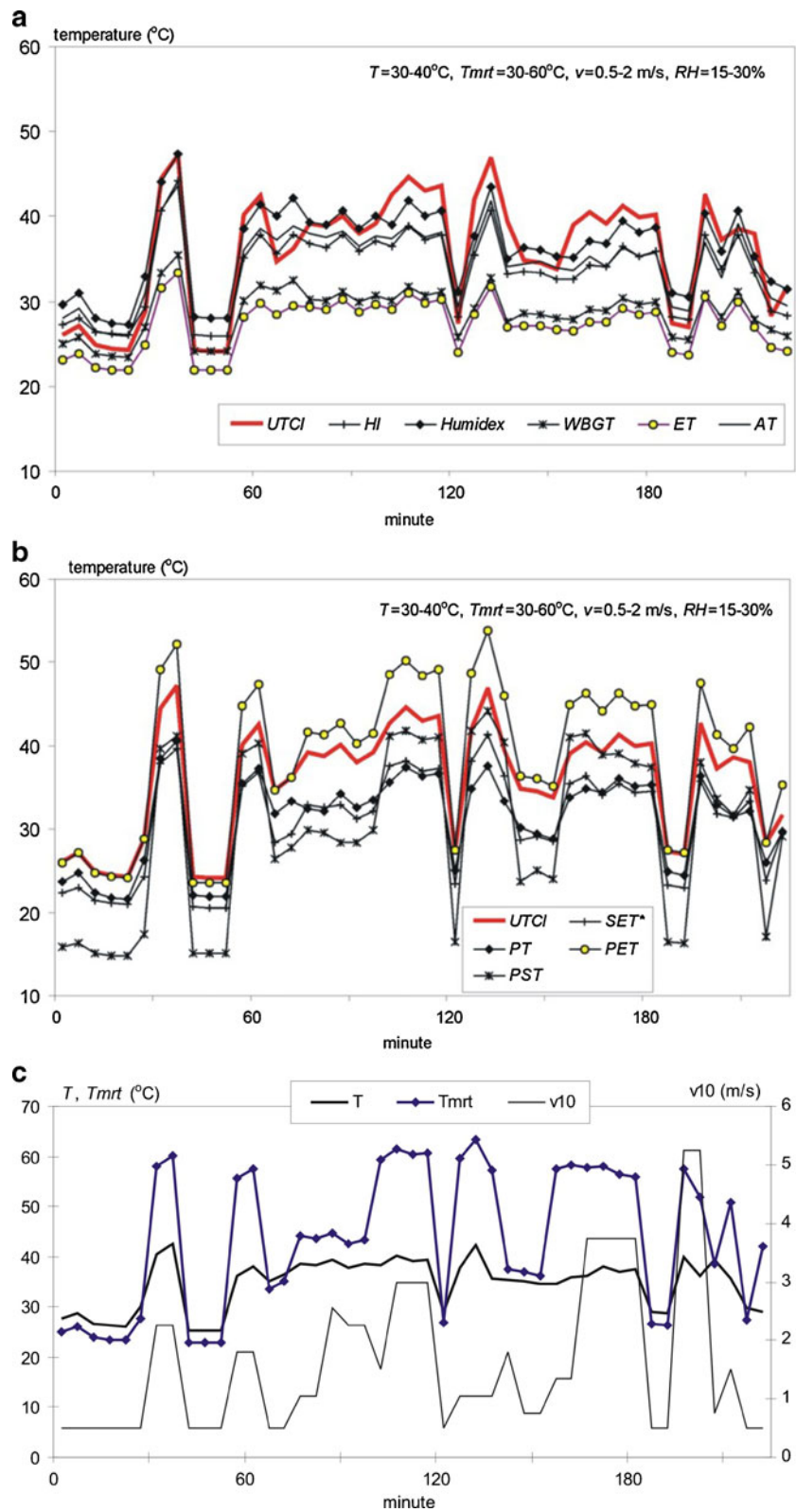
UTCI. The higher PT values compared to UTCI in this humid subtropical climate, and lower in the dry subtropical climate of Negev desert (Fig. 10) demonstrate the higher humidity sensitivity in thermal assessment by PT. SET* is

also derived from the Gagge et al. (1986) two node model, but tends to be lower than air temperature by 1–2 K. SET* applies a noticeable lower activity (factor 1.5) and possibly a higher water vapor permeability of clothing than PT, and

Fig. 11 Changes of UTCI and other bioclimatic indices during a 6.5-h experiment on central Madagascar in wet subtropical climate, 22 August 2007; *lower panel* course of meteorological variables (*T*, Tmrt, v10)
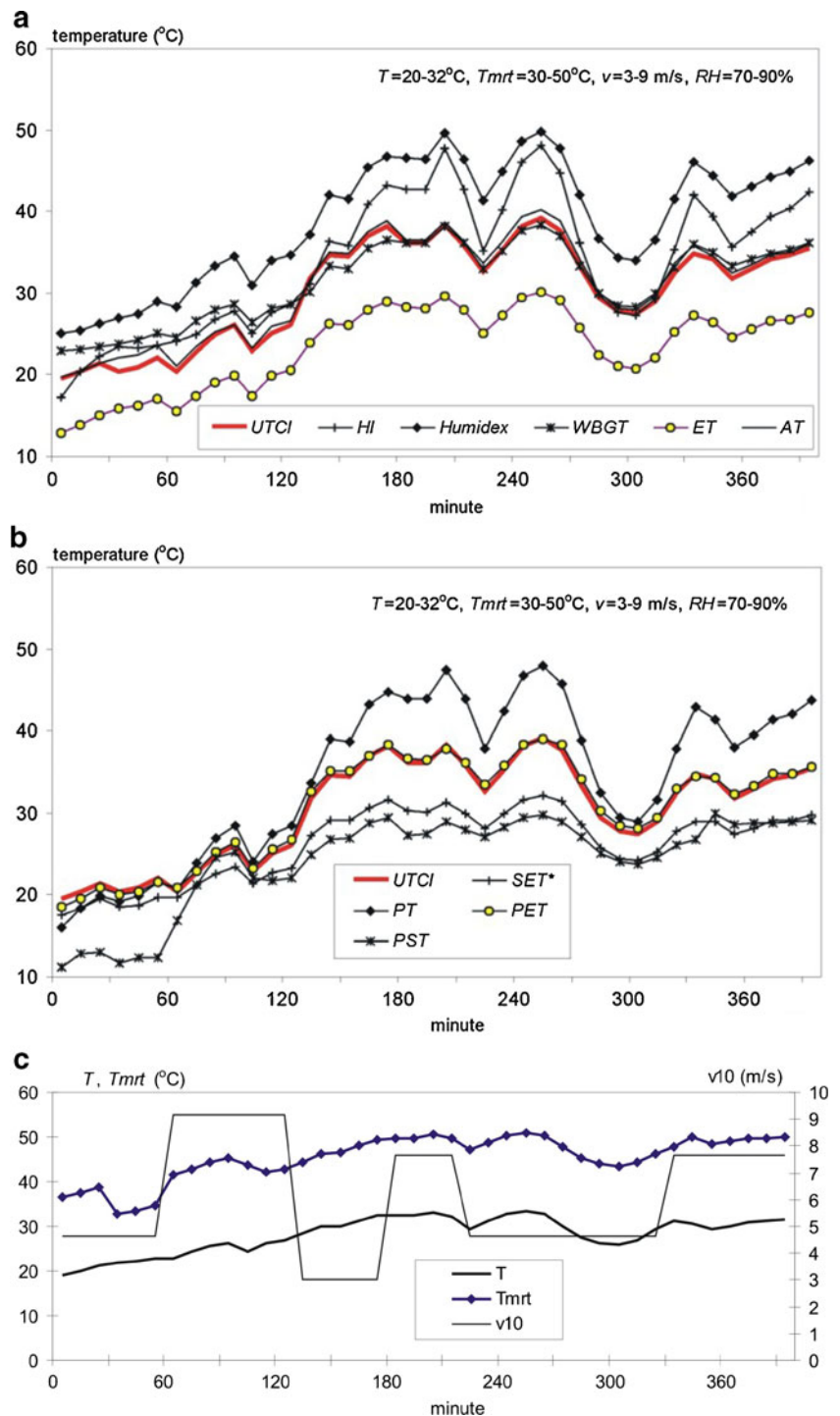

thus, the equivalent temperature is also reduced compared to UTCI.

Cities and urbanized areas have specific climatic conditions. The most important features of urban climate are: the urban heat island, reduction of wind and great spatial differences of solar radiation penetrating to the bottoms of street canyons. This is well illustrated by an experiment carried out in the centre of Warsaw (Poland) on

12 October 2007. The measurements were made in a narrow (10 m), deep (30 m) street canyon. Due to low sun altitude, solar rays reached street level for a very short period (from 10.00 until 11.00 a.m. and from 1.00 until 3.00 p.m.). UTCI values were very sensitive to the temporal changes in Tmrt and wind speed. Among the other indices only ET and SET* simulated such fluctuations in bioclimatic conditions. Comparing the values of various indices,

Fig. 12 Changes of UTCI and other bioclimatic indices in Warsaw downtown, in moderate transient climate, 12 October 2007; *lower panel* indicates course of meteorological variables (*T*, Tmrt, v10)
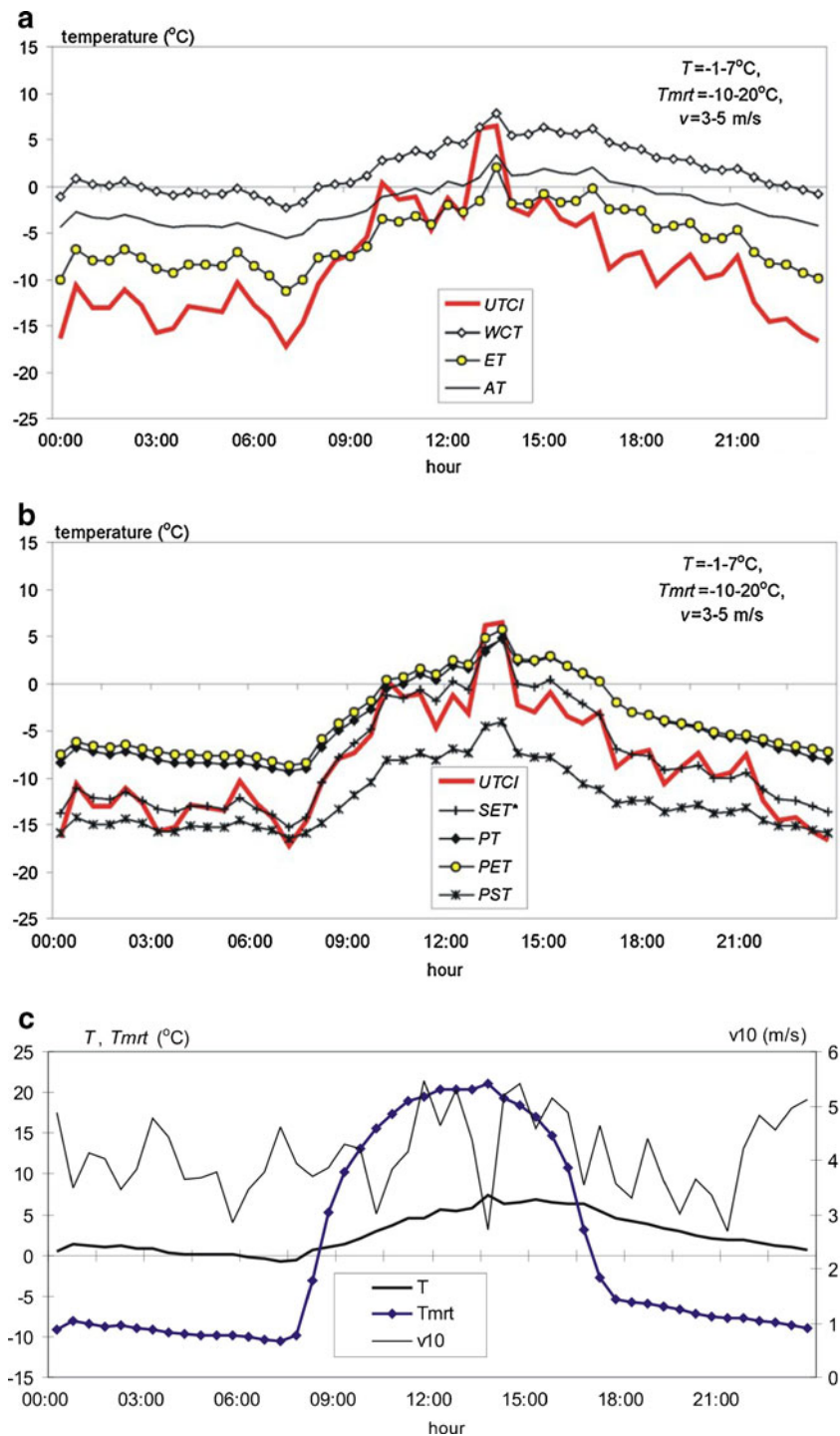
WCT, AT, PT and PET were higher and PST lower then UTCI. The closest to UTCI was SET* index (Fig. 12).

Conclusions

All the indices that were derived from various human heat budget models (PET, PT, SET*, PST, PhS) correlated very well with UTCI (the lowest R^2 coefficient was 93.1). The indices based on relatively simple formulas (HI, AT, Humidex, WBGT, WCT) correlated less with UTCI. An exception was ET, with an R^2 coefficient of 96.7. One of the possible causes in unconformity is the lack of radiation factor in the equations. HI, Humidex and WCT do not have the radiation options of formulas. However, for WBGT and

AT, non-radiation equations are used more widely in bioclimatic research than their radiation options.

The best relationships with UTCI were found for SET*, ET and PT indices; they represented high correlation coefficients with slopes of regression lines close to 1. A high correlation was also observed for PMV and PhS indices.

From the synoptic and microclimatic data it can be deduced that particular indices express bioclimatic conditions reasonably only in specific situations. UTCI, on the other hand, is an index that represents various climates, weather and locations very well. Furthermore, UTCI is very sensitive to changes in ambient stimuli: temperature, solar radiation, humidity and especially wind speed; in this respect, it represents the response of the human body. In contrast, the HI, Humidex, AT, PET and PT indices are more closely related to air temperature, especially as their assumptions on clothing insulation differ strongly from the state-of-the-art clothing model used in UTCI. ET, SET* and PST are noticeably more sensitive to the cooling effect of the wind.

In terms of the microclimatic scale, UTCI represents the temporal variability of thermal conditions better than the other indices. It reflects even slight differences in the intensity of meteorological stimuli.

In conclusion, the analyses presented in this paper indicate the universal nature of UTCI by its ability to represent bioclimatic conditions in terms that are applicable to human strain under a wide range of climatic conditions.

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