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UTCI: VALIDATION AND PRACTICAL APPLICATION TO THE ASSESSMENT OF URBAN OUTDOOR THERMAL COMFORT

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Abstract

We introduce here the structure and elements to the recently-developed Universal Thermal Climate Index (*UTCI*), as well as operational procedure relating to it. This is then followed by a demonstration of how the *UTCI* can be applied to bioclimatic surveys, using data from a study carried out in the sub-tropical urban area of Curitiba, Brazil. The empirical data from that were found to confirm the assumptions behind the *UTCI* model, which also supplied adequate predictions of pedestrians' behaviour as regards clothing and thermal sensation. Finally, in the context of urban planning, we show that the *UTCI* captures the influence of the design characteristics of streets and public spaces on urban microclimate, and its impact on pedestrian thermal comfort.

Key words

human biometeorology • climate index • model • urban planning

Introduction

Within the framework of the recently-completed European COST Action 730, the Universal Thermal Climate Index (*UTCI*) has been made available as an operational procedure by which to assess the outdoor thermal environment from the point of view of the core fields of human biometeorology. As the rationale and development of the *UTCI* have already been reviewed elsewhere (Błażejczyk et al. 2010; Jendritzky et al. 2012), and are indeed described in this very issue (see article in the current issue Błażejczyk et al. 2013), we will here confine ourselves to just a brief summary of the *UTCI* concept and basics, as illustrated in Figure 1.

The aim of the *UTCI* has been to make available an index (i.e. a one-dimensional characteristic) for an assessment of the outdoor thermal environment that integrates the interaction of air temperature, wind speed, humidity and radiation fluxes on the human thermo-physiological state in terms of equivalent temperature. This involved the definition of a reference environment with 50% relative humidity (but vapour pressure not exceeding 20 hPa), still air and radiant temperature equalling air temperature, to which all other climatic conditions are compared. Following extensive validation work (Psikuta et al. 2012), the simulated dynamic response of a thermo-physiological model (Fiala et al. 2012), as integrated with a behavioural clothing model (Havenith et al. 2012), was used to derive this equivalent temperature scale and to establish *UTCI* threshold values that define different categories of thermal stress.

Furthermore, to facilitate the widespread use of the *UTCI*, the operational procedure (Bröde et al. 2012a) provides simplified algorithms with which to compute *UTCI* values from air temperature (*Ta*), wind speed (*va*), mean radiant temperature (*Tmrt*) and water vapour pressure (*pa*), as input by a table-lookup approach or by regression equations. Both simplified methods were based on data matrices generated by running physiological simulations over a grid of relevant meteorological conditions defined by combinations of *Ta*, *Tmrt*, *va* and *pa* (Fig. 1).

The *UTCI* should be applicable universally to different geographical scales (global, regional, local), and to all seasons and climates from extreme cold to extreme heat. It should serve as an internationally standardised tool for assessing the thermal environment in the core fields of human biometeorology including weather services, heat- or cold-warning systems related to public health, epidemiological research, or precautionary planning in urban areas (Jendritzky et al. 2012).

The provision of expert support to urban planning through outdoor weather assessment is one of the key application areas of human biometeorology (Vanos et al. 2010). Adequate modifications of the urban-area configuration may do much to improve outdoor thermal conditions, and thus influence the use of public spaces in a positive way. For instance, field observations or predictions of human responses can quantify the impacts of the urban geometry on outdoor thermal comfort, e.g. through the design of comfortable shaded or sun-lit areas in urban spaces for pedestrian use (Johansson & Emmanuel 2006), or with assessment of the potential influences of climate change on urban spaces (Thorsson et al. 2011). Once a link is established between urban planning aspects and the resulting outdoor thermal environment, with the corresponding human reactions, such places can be improved accordingly using numerical simulation (Ali-Toudert & Mayer 2006) or geographic information systems (Oka 2011). In this context, the *UTCI* may serve as a state-of-the-art tool for the biometeorological assessment of these microclimates in physiologically relevant terms (Jendritzky et al. 2012). However, in recognition of its novelty, the *UTCI* must be tested further from the point of view of urban planning (McGregor 2012).

Objectives

The aim of the research detailed here in the context of urban planning was to study the applicability and suitability of the *UTCI* to the prediction of thermal comfort votes in urban areas.

Special attention was paid here to the question of which of two stress categories on the *UTCI* equivalent temperature scale (Fig. 1) should be chosen as reference for urban outdoor thermal comfort studies, the choice being between: (i) the category 'no thermal stress' 9°C≤*UTCI*≤26°C or (ii) the sub interval 18°C≤*UTCI*≤26°C. The latter had previously been shown (Bröde et al. 2012a) to comply with the definition of the 'Thermal Comfort Zone' (TCZ) given by the Glossary of Terms for Thermal Physiology (The Commission for Thermal Physiology of the International Union of Physiological Sciences 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*".

We were further interested in determining whether and to what degree the *UTCI* would be able to reflect the impact on thermal comfort by urban geometry defined by site characteristics like the sky view factor (*SVF*), which for a given site indicates the degree of obstruction of sky by the surroundings (Grimmond et al. 2001), or the height-to-width ratio (*H/W*), which expresses the relationship between average building height (*H*) and street width (*W*), both factors known to have an influence on urban microclimate (Oke 1981).

Our approach was to use data obtained from outdoor comfort surveys with pedestrians in Curitiba, Southern Brazil (Krüger et al. 2010), and to extend earlier analyses (Bröde et al. 2012b), by enlarging the database and considering the influ-

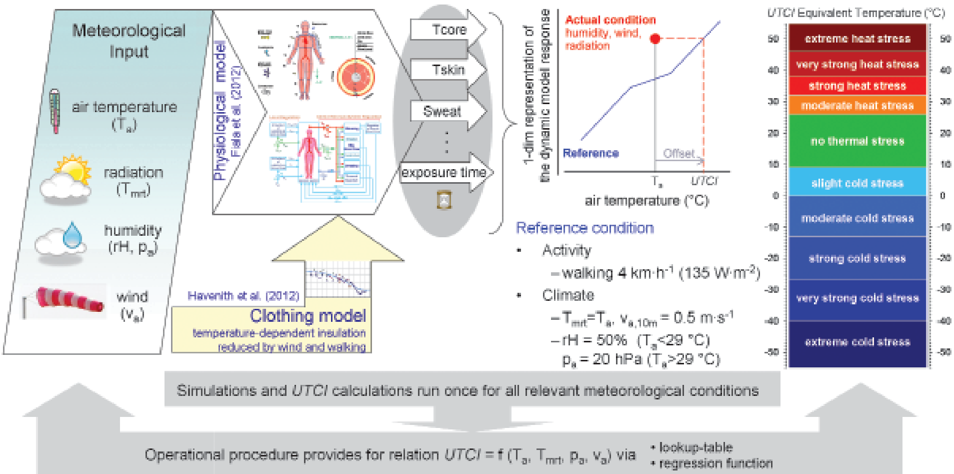

Figure 1. Elements of the operational procedure and concept of the *UTCI* as categorized equivalent temperature derived from the dynamic response of a thermo-physiological model coupled with a behavioural clothing model.

ence of urban geometry as characterised by *SVF* and *H/W* ratios (Krüger et al. 2011).

Study area

Curitiba is a city of 1.8 million inhabitants located in southern Brazil (at 25°26'S, 49°16'W), at an altitude of 917 m a.s.l. It has a subtropical climate (according to Koeppen-Geiger's Climate Classification System, 'Cfb'), with average temperatures between 17 and 20°C in summer and 12 and 14°C in winter. Annual average temperature is around 16°C and the daily temperature swing ranges between 0.5 and 25.7 K (Krüger & Rossi 2011). The survey was carried out at fifteen different sites along the pedestrianised area around '15th of November Street' (*Rua XV de Novembro*).

Survey data base

During several campaigns run between January and August 2009, and in June 2010, data were collected during daytime (10:00 to 15:00) from 1,685 pedestrians, of whom 960 (57%) were males. The participants were permanent residents, i.e. had been living for longer than 6 months in Curitiba; and their ages ranged from 13 to 91 yrs, with a mean ±SD of 38 ±17 yrs.

In structured interviews (Krüger et al. 2010), passers-by provided information on their weight, height, age and gender, on their worn clothing – – from which thermal insulation was estimated according to ISO 9920 (2007), as well as on their thermal sensation, affective evaluation regarding comfort, thermal preference and thermal tolerance using standardized scales (ISO 10551 1995). Measurements of air temperature, of mean radiant temperature, humidity (relative humidity (*rH*), water vapour pressure), as well as of wind speed were made *in situ*, and in parallel with interviews using the transportable HOBO® (Onset Computer Corporation, Pocasset, MA) weather stations. These were equipped with a three-cup anemometer measuring wind speed at approximately 2.1 m height, air temperature and relative humidity sensors at 1.1 m, a silicon pyranometer measuring global solar radiation at 1.6 m and a copper globe thermometer at 1.1 m painted with RAL-7001 (gray) whose recordings were used to calculate mean radiant temperature (*Tmrt*) (Thorsson et al. 2007). It was from those measurements, with the wind speed measured at 2.1 m height scaled-up to the required input at 10 m above ground level in lien with the logarithmic formula LOG(10/0.01)/LOG(2.1/0.01) provided by the operational procedure (Bröde et al. 2012a), actual *UTCI* values were calculated.

Site characteristics such as building height and street width were used to calculate height-to-width ratios (*H/W*). The sky view factors (*SVF*) were determined from fisheye photographs taken at each survey point (Tab. 1) and post-processed using the RayMan software (Krüger et al. 2011; Matzarakis et al. 2010). For the purposes of this study, the two contrasting groups of sites were taken to be: street canyons, in which about two-thirds of the interviews took place, and which were characterised by higher *H/W* ratios and lower *SVF* values, and open spaces or crossroads with higher *SVF* and lower *H/W* ratios (Tab. 1).

For the analysis of thermal comfort, the statistical significance of the association between the votes on the 7-point scale of thermal sensation (from -3:'cold' via 0:'neutral' to +3:'hot') and on the 4-point scale of affective evaluation (0:'comfortable', 1:'slightly uncomfortable', 2:'uncomfortable', 3:'very uncomfortable') was assessed by means of Fisher's Exact Test (Mehta & Patel 1983). Further, the respondents were classified into three categories of thermal comfort, with comfort defined as a thermal sensation vote of 0 ('neutral') or an affective evaluation vote of 0 ('comfortable') (Tab. 2) and with corresponding definitions for 'cold discomfort' (sensation<0 & evaluation>0) and 'warm discomfort' (sensation>0 & evaluation>0), respectively. Probabilities for those ordered three categories (cold discomfort, comfortable/neutral, warm discomfort) predicted by the *UTCI* were computed by ordinal logistic regression (Harrell 2001).

Table 1. Range of sky view factors (*SVF*) and height-to-width ratios (*H/W*), number of observations (*n*), averaged errors (*bias*), root mean squared errors (*rmse*) and Pearson correlation coefficients (*r*) of the observed thermal sensation votes compared towith the dynamic thermal sensation predicted byusing the *UTCI*-Fiala model in relation to the site characteristics.

Site characteristics	Example fisheye photo	*SVF* range	*H/W* range	*n*	*bias*	*rmse*	*r*
Open spaces / Crossroads		0.34-0.55	<0.8	580	0.03	0.98	0.68
Street canyons		0.20-0.32	1.1-2.3	1105	-0.22	0.95	0.59
Total sample		0.20-0.55	<0.8-2.3	1685	-0.13	0.96	0.62

Data analysis and statistics

To describe the average course of microclimatic measurements, of clothing thermal insulation and of thermal sensation, while considering the potentially non-linear relationships with environmental temperature and the *UTCI*, respectively, general additive models with locally estimated smoothing functions (LOESS) and 95%-confidence bands were computed, separately for open spaces and street canyons (Zuur et al. 2009).

The observed thermal-sensation votes were compared with the dynamic thermal sensation (DTS) predicted using the *UTCI*-Fiala model (Fiala et al. 2012), as obtained for the *UTCI* reference environment and averaged over 0.5, 1, 1.5 and 2 h exposure times (Bröde et al. 2012b). The goodness-of-fit for the whole sample and for the different subgroups was assessed by reference to the averaged error (*bias*), with the error calculated as the difference between predicted and observed values, by the root mean squared error (*rmse*) and by the Pearson correlation coefficient (*r*) between observed and predicted values.

Results

Microclimate measurements are illustrated in Figure 2 in relation to the site characteristics and to air temperature, which varied across the range 6–32°C. Only light air movements with averaged wind speed between 1.0 and 1.5 m·s^{-1} were observed, and these did not vary in a consistent manner in line with air temperature. There were no significant differences between open spaces and street canyons in terms of either wind speed or humidity. Relative humidity (*rH*) stayed within the limits of 50-60% on average, with vapour pressure rarely exceeding 20 hPa at higher temperatures. Radiant heat load expressed as the difference between mean radiant temperature and air temperature (Δ*Tmrt*=*Tmrt*-*Ta*) showed a bimodal distribution. On the one hand, the frequent occurrence of shaded conditions was reflected in a cluster of near-zero values for Δ*Tmrt*. On the other hand, under solar load, values of Tmrt up to 50 K above Ta were observed. Values of Δ*Tmrt* in open spaces were significantly increased over those in street canyons, by 13 K averaged over the range of air temperatures (Fig. 2, mid panel). Consequently, *UTCI* values were significantly higher, on average by about 4 K, in open spaces than in street canyons (Fig. 3, left panel).

Clothing thermal insulation showed considerable individual-to-individual variability (Fig. 3, right panel). However, on average a distinct trend for decreasing insulation with increasing air temperature emerged, and was in good agreement with the *UTCI*-clothing model for cool and warm conditions, not differing significantly between open spaces and street canyons. Only around 22°C were slight differences with mean deviations of about 0.2 clo observed, these being related to a measurement campaign run in street canyons during the cold season, with people wearing winter clothing at air temperatures above 20°C (Bröde et al. 2012b).

Thermal sensation votes also exhibited large inter-individual variability and an approximately linear trend for more distinct sensations of warmth with increasing temperature, as well as cooler sensations with decreasing temperature, as illustrated by the left panel of Fig. 4. Corresponding to the higher values of mean radiant temperature (Fig. 2) and of the *UTCI* (Fig. 3) for open spaces, thermal sensation votes were also on average 0.3 scale units higher than those for street canyons. The right panel of Table 4 looks at thermal sensations in relation to the *UTCI*, and reveals that the differences between open spaces and street canyons were diminished in the region of cool and warm sensations. In the 'neutral' range, the sensations for open spaces were even of slightly lower value than for street canyons, on average by 0.2 units on the seven-point scale.

The average thermal sensation response was well approximated by the dynamic thermal sensation predicted by the *UTCI*-Fiala model (Fiala et al. 2012) for the *UTCI* reference environment (Fig. 4, right panel). The bias was negligible, with *rmse* less than 1 unit on the seven-point scale; and the correlation coefficient was about 0.6 for the whole sample as well as for the subsamples obtained from open spaces and street canyons (Tab. 1).

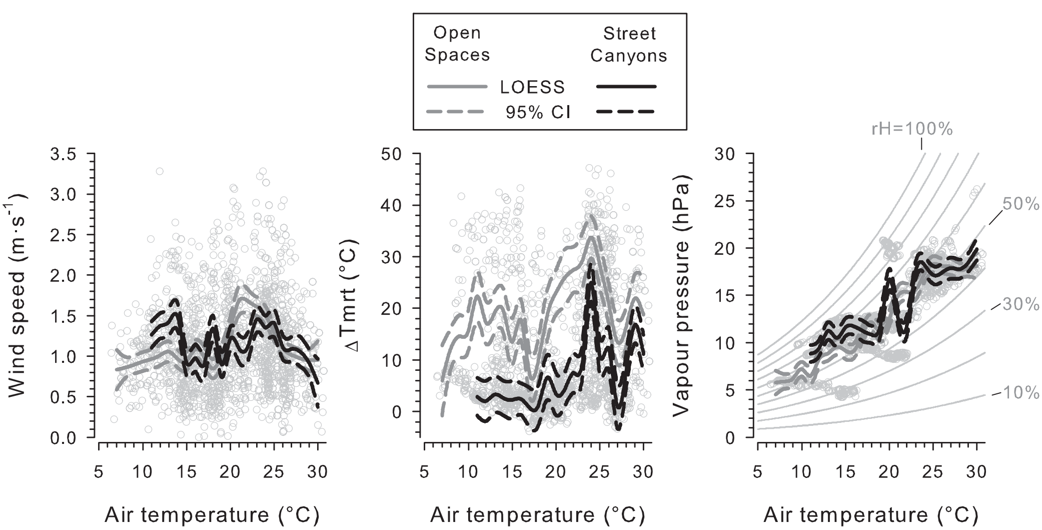

Figure 2. Individual microclimatic measurements (grey circles) of wind speed (left panel), of the difference of mean radiant to air temperature (Δ*Tmrt*, mid panel) and of humidity (right panel), in relation to air temperature. Mean curves with 95% confidence intervals (CI) for open spaces and street canyons, respectively, were obtained fromby fitting locally estimated smoothing splines (LOESS).

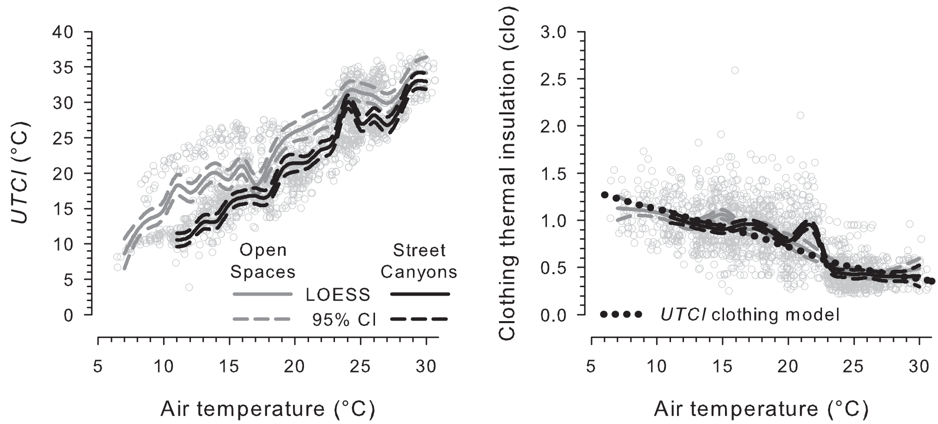

Figure 3. Individual values of the *UTCI* (left panel) and clothing thermal insulation (right panel), as related to air temperature. Mean LOESS curves with 95% confidence bands for open spaces and street canyons (Fig. 2) are added, as well as the predicted clothing insulation (dotted line, right panel) from the *UTCI*-clothing model.

The analysis of thermal comfort was based on the cross tabulation of thermal sensation and affective evaluation with respect to comfort. The contingency Table (Tab. 2) showed a highly significant association between thermal sensation and affective evaluation (Fisher's Exact Test $p<0.001$). From 1,685 interviewees, 1210 (72%) persons voted 'neutral' on the sensation scale or 'comfortable' on the affective scale, with more than one-third of votes indicating concomitant sensations of neutral and comfortable (Tab. 2). 188 pedestrians (11%) claimed to be experiencing 'cold discomfort', while 287 (17%) indicated 'warm discomfort'.

Figure 5 presents the probabilities for the three ordered categories of thermal comfort predicted by the *UTCI*, as calculated using ordinal logistic regression. Diagnostic tests on the goodness-of-fit of the ordinal logistic regression model confirmed that the proportional odds assumption underlying the model was tenable (1-df chi-square=0.07, $p=0.80$), that the influence of the explanatory variable *UTCI* was highly significant ($p<0.001$), and that the predictive ability of the model was reasonable, as indicated by the value of 0.780 for the concordance index c of rank correlation. As expected, the regression model predicted higher probabilities of cold discomfort for decreasing *UTCI* values,

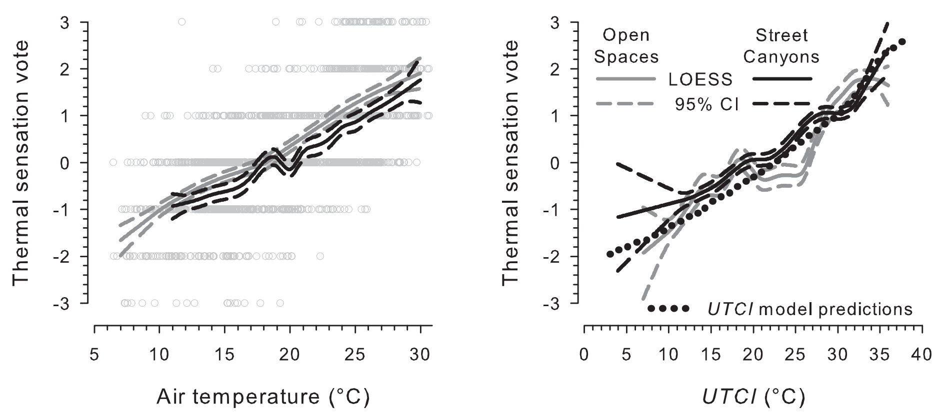

Figure 4. Individual thermal sensation votes with mean LOESS curves and 95% confidence bands for open spaces and street canyons in relation to air temperature (left panel) and the mean curves only in relation to the *UTCI* (right panel), respectively. The dotted line in the right panel shows the dynamic thermal sensation predicted by the *UTCI*-Fiala model for the reference conditions (Fig. 1).

Table 2. Contingency table with frequencies and percentages (in brackets) observed for categories of thermal sensation (sl.='slightly') and affective evaluation. Colouring of cells indicates neutral or comfortable values (grey), cold discomfort (dark grey), and warm discomfort (light grey), respectively.

Affective evaluation	Thermal sensation							Frequency (percentage)
	-3 cold	-2 cool	-1 sl. cool	0 neutral	1 sl. warm	2 warm	3 hot	row totals
Comfortable: 0	1 (0.1)	34 (2.0)	173 (10.3)	597 (35.4)	229 (13.6)	74 (4.4)	9 (0.5)	1117 (66.3)
Sl. uncomfortable: 1	8 (0.5)	42 (2.5)	103 (6.1)	87 (5.2)	109 (6.5)	86 (5.1)	30 (1.8)	465 (27.6)
Uncomfortable: 2	9 (0.5)	11 (0.7)	10 (0.6)	6 (0.4)	7 (0.4)	27 (1.6)	20 (1.2)	90 (5.3)
Very uncomfortable: 3	0 (0.0)	3 (0.2)	2 (0.1)	0 (0.0)	1 (0.1)	1 (0.1)	6 (0.4)	13 (0.8)
Column Totals	18 (1.1)	90 (5.3)	288 (17.1)	690 (40.9)	346 (20.5)	188 (11.2)	65 (3.9)	1685 (100.0)

as well as higher probabilities of warm discomfort with increasing *UTCI* (Fig. 5). Consideration of the probability curves for the individual categories of thermal comfort in relation to the *UTCI* assessment scale suggested *UTCI*=18°C as a suitable lower boundary for comfort, since the probability for comfort was above 80%, whereas the upper boundary appeared to be somewhat lower than the 26°C recommended by the *UTCI*. However for the narrow 'Thermal Comfort Zone' (TCZ) the probabilities for both cold and warm discomfort remained below 20% (Fig. 5).

Discussion

The *UTCI* was developed under EU COST Action 730 (Błażejczyk et al. 2010, 2012; Jendritzky et al. 2012), as an equivalent temperature assessing the physiological response to outdoor thermal conditions ranging from extreme cold to extreme

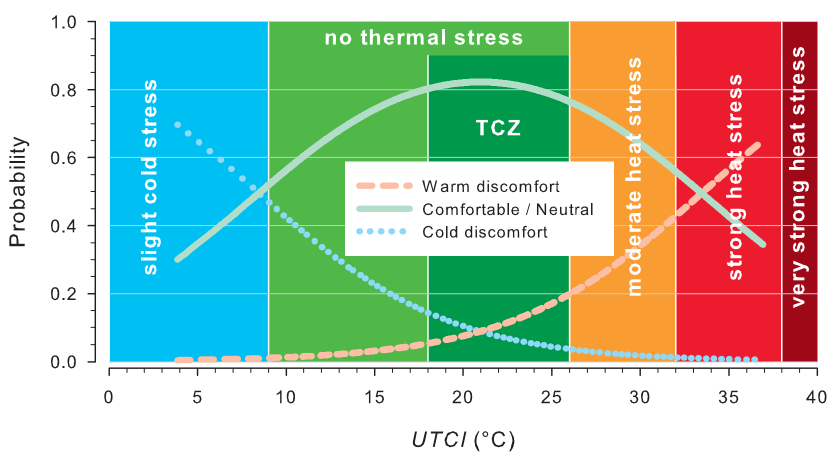

Figure 5. Probabilities of the individual categories of thermal comfort predicted by ordinal logistic regression analysis with *UTCI* as explanatory variable. Also shown are the boundaries of the thermal stress categories from the *UTCI* assessment scale and the sub range of *UTCI* values compliant to the definition of the 'Thermal Comfort Zone' (TCZ) by the *Glossary of Terms for Thermal Physiology* (The Commission for Thermal Physiology of the International Union of Physiological Sciences 2003).

heat. It is based on complex models of clothing behaviour (Havenith et al. 2012) and human thermoregulation (Fiala et al. 2012). The latter was validated extensively using independent experimental data (Psikuta et al. 2012). The simplified computing algorithms provided by the operational procedure (Bröde et al. 2012a) are aimed at facilitating widespread use of the *UTCI* in core fields of human bioclimatology, including urban planning as analysed by this study on pedestrian thermal comfort.

The special feature of the survey data in this study are the microclimatic recordings carried out *in situ* and in parallel with interviews. This allowed for the testing of assumptions as regards the *UTCI*, and its predictive capabilities, free from the interference due to errors that may be introduced when microclimate data, especially for mean radiant temperature, have to be estimated from meteorological observations (Weihs et al. 2012). The dependence of clothing insulation on air temperature found in this survey in a subtropical area agreed well with the relationship developed from European data for the *UTCI,* and thus corroborates the assumptions of the *UTCI*-clothing model (Havenith et al. 2012). The minor differences relating to some persons wearing winter clothes at higher temperatures may reflect seasonal adaptation (Lin et al. 2011). The course of humidity relating to air temperature, and the high frequency of shaded situations, support the conditions of humidity and of radiant load chosen as reference environment for the *UTCI* (Bröde et al. 2012a).

Clothing insulation and thermal sensations observed in this survey conducted in a subtropical area were well predicted by the *UTCI*'s models of clothing and thermo-physiology, respectively. This suggests that, although being predominantly developed from European data, the *UTCI* may also be useful in sub-tropical urban areas. In addition, the results of the ordinal logistic regression analysis on thermal comfort did not suggest the vital need for a re-calibration of the *UTCI* assessment scale by adapting the threshold values between the different thermal stress categories. In fact, the sub-range 18°C≤*UTCI*≤26°C emerged as a suitable reference category describing the 'Thermal Comfort Zone' in urban areas.

Urban geometry, as here confined to the contrast between open spaces and street canyons, showed the expected influence on the microclimate. In open spaces with less sky obstruction (as indicated by higher *SVF*), solar irradiation and consequently mean radiant temperatures were higher when considered in relation to air temperature (Ali-Toudert & Mayer 2006; Johansson & Emmanuel 2006; Thorsson et al. 2011). This was reflected in increased *UTCI* values conditional on air temperature for open spaces compared with street canyons. These effects on microclimate were accompanied by higher votes for thermal sensation in open spaces, when these are plotted against air temperature. As identical index values for the *UTCI* should represent identical physiological strain (Jendritzky et al. 2012), differences in thermal sensations attributable to urban geometry might be expected to disappear or at least be diminished, when considered in relation to the *UTCI*. This compensatory effect was confirmed by the analysis presented in the right panel of Figure 4. Furthermore, the small differences between open spaces and street canyons in bias, rmse and correlation from the goodness-of-fit analysis of thermal sensations predicted by the *UTCI*-Fiala model (Tab. 1) were negligible and of similar magnitude as had been observed recently for subgroups defined by gender, age or body-mass-index (Bröde et al. 2012b). These outcomes demonstrate that the *UTCI* absorbed the effects of urban geometry on thermal sensation.

Conclusions

The results of this study sustain the conclusion that the *UTCI* has the potential to become a useful tool in the field of urban planning, when it comes to assessing the combined influence of ambient temperature, wind, humidity and radiant heat fluxes on outdoor thermal comfort, while:

- being based on the most recent scientific progress in both thermo-physiology and heat exchange theory,
- being easily applicable in numerical simulations or GIS-based applications,
- capturing the effects of street-design characteristics on the urban microclimate and on thermal comfort.

The results of the study furthermore reveal that, in comparison with the category entitled 'no thermal stress' (with *UTCI* equivalent temperatures between 9 and 26°C), the sub-range between 18–26°C better describes the 'Thermal Comfort Zone' and constitutes a suitable reference category for this scope of application. The semantic labelling assigned to the heat- and cold-stress categories will, however, require additional validation, using data from further surveys and epidemiological studies.

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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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