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Predicting outdoor thermal sensation from two field studies in Curitiba, Brazil and Glasgow, UK using the Universal Thermal Climate Index (UTCI)

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Abstract

We present a comparative analysis of outdoor human thermal sensation against predictions with the Universal Thermal Climate Index (UTCI) for two sets of data collected in Curitiba, Brazil (subtropical climate in elevation) and in Glasgow, UK (maritime temperate climate). Surveys took place during daytime in pedestrian areas with microclimate measurements and concurrent administration of thermal sensation and preference questionnaires. Comparisons were made with regard to clothing levels (predicted by UTCI's clothing model versus actual garments observed) and votes of thermal sensation in relation to ambient temperature variations and to UTCI values. Results suggest that clothing levels are fairly well predicted by UTCI's clothing model for both cases. A small offset was noticed for Glasgow from the onset of the summer period, with UTCI overestimating actual clothing. More noticeable however were differences between clothing levels for Curitiba and Glasgow for the same ambient temperature range (roughly 15-20°C), which is also reflected on the thermal sensation votes for both locations. As those divergences are found for the start of the summer period in Glasgow, it is suggested that people under those climatic conditions accept lower air temperatures and indeed regard those as comfortable presumably due to acclimatization. For calculated UTCI, similar discrepancies have been observed for both cases, with a slight overestimation of actual thermal sensation for Curitiba and a slight underestimation of actual thermal sensation for Glasgow.

Keywords: outdoor comfort surveys, thermal comfort index, thermal sensation, UTCI.

Introduction

Outdoor comfort indices can be important tools for urban planning, as they provide an integrated approach to the evaluation of thermal conditions in outdoor spaces. Once a set of site-specific climatic conditions are known (by means of in situ measurements or from predicted data from computer simulations), outdoor comfort/discomfort can be more comprehensively assessed than using the simple UHI approach or ambient temperature estimates, therefore facilitating the analysis of existing linkages between urban morphology and microclimate conditions. Relevant for the correct adoption of a given index is an overall check of its applicability and limitations for the location under consideration. The present paper is concerned with the applicability of the recently developed outdoor thermal comfort index UTCI ('Universal Thermal Climate Index') for two locations with quite distinct climatic and socio-cultural patterns. Data gathered from extensive campaigns conducted in both locations throughout outdoor comfort surveys are compared to UTCI predictions. Finally, the two data sets are compared to each other with regard to clothing levels (predicted by UTCI's clothing model versus actual garments observed) and votes of thermal sensation in relation to ambient temperature variations and to UTCI values.

UTCI aims at assessing the outdoor thermal conditions in the major fields of human biometeorology by a one-dimensional quantity summarising the interaction of environmental temperature, wind speed, humidity and of the long-wave and short-wave radiant fluxes. This assessment should be based on the physiological response of the human body, which in turn was to be simulated by a thermo-physiological model. For this purpose, based on an advanced multi-node model of human thermoregulation (Fiala et al., 1999; Fiala et al., 2001; Fiala et al., 2003; Fiala et al., 2010) the 'UTCI-Fiala' model of thermo-physiological comfort was derived (Fiala et al., 2011) and coupled with a state-of-the-art clothing model (Havenith et al., 2011). This model considers (i) the behavioural adaptation of clothing insulation observed from European field studies for the general urban population in relation to the prevailing environmental temperature, (ii) the distribution of the clothing over different body parts, and (iii) the reduction of thermal and evaporative clothing resistances caused by wind and the movement of the wearer, who is assumed walking at 4 km/h on the level.

Similar to other indices employed to the assessment of outdoor thermal conditions, such as the commonly used PET index ('Physiologically Equivalent Temperature') (Höppe, 1999), UTCI adopts the concept of an equivalent temperature. This involved the definition of a reference environment with 50% relative humidity (but vapour pressure not exceeding 20 hPa), with still air and radiant temperature equalling air temperature, to which all other climatic conditions are compared. Equal physiological conditions are based on the equivalence of the dynamic physiological response predicted by the model for the actual and the reference environment. As this dynamic response is multidimensional (body core temperature, sweat rate, skin wettedness etc. at different exposure times), a strain index was calculated by principal component analysis as single dimensional representation of the model response. The UTCI equivalent temperature for a given combination of wind, radiation, humidity and air temperature is then defined as the air temperature of the reference environment, which produces the same strain index value (Bröde et al., 2011a).

In this paper, we present a comparative analysis of outdoor human thermal sensation against predictions with the Universal Thermal Climate Index (UTCI) for two sets of data gathered from outdoor comfort surveys in Curitiba, Brazil (subtropical climate in elevation) and in Glasgow, UK (maritime temperate climate).

Outdoor Comfort Surveys

In both locations, the surveys were carried out in pedestrian areas during day time by a team of researchers equipped with 'portable' weather stations and a standard comfort questionnaire. The procedures adopted do not vary significantly as one of the authors was the team leader on both field studies, with the aim of establishing comparisons of research outcomes.

In Curitiba, measurements were taken between January and August 2009, over 14 days of sampling. Measurements were carried out at two points each day, spanning up to five hours (typically from 10am to 3pm local time). Two HOBO® weather stations (Onset Computer Corporation, Pocasset, MA) were used (Figure 1a), equipped with a three cup anemometer at approximately 2.1 m height, air temperature and relative humidity sensors at 1.1 m, a copper gray-colored globe thermometer at 1.1 m and a silicon pyranometer measuring global solar radiation at 1.6 m. Data from all sensors were recorded every five seconds and averaged over one minute.

In Glasgow, climate measurements and field surveys were carried out between March and July 2011, over 19 outdoor survey campaigns. Each measurement/survey campaign spanned up to three hours (from 10am to 1pm, local time). Climate measurements employed a Davis Vantage Pro2 weather station (Figure 1b), equipped with a three cup anemometer (at approximately 1.5 m above ground), air temperature and humidity sensors at 1.1 m above ground and a silicon pyranometer at 1.4 m. Additionally, a globe thermometer was prepared for assessing the mean radiant temperature, which consisted of a gray sphere with an enclosed temperature data logger (Tinytag-TGP-4500), attached to the tripod at 1.1 m above ground. Data from all sensors were registered by a wireless data logger every five seconds and averaged over one minute.

a) b)

Figure 1: Equipment used for microclimatic measurements: a) in Curitiba; b) in Glasgow

In both cases, monitored climatic variables fulfil the recommendations on accuracy according to ISO 7726 (ISO 7726, 1998). The mean radiant temperature (Tmrt in °C) was calculated from globe temperature measurements (Tg in °C), and taking into account wind speed (Va in m/s), air temperature (Ta in °C), and the globe's emissivity (εg) and diameter (D in m), respectively, according to ISO 7726 (1998) for forced convection. The exact times when surveys were conducted were subsequently used to match the inquired responses to the corresponding microclimatic data.

Even though both climates receive the same classification according to Koeppen-Geiger's Classification System, "Cfb", Curitiba (25°26′S, 49°16′W, 917m amsl) is greatly affected by its geographical location, close to the Tropic of Capricorn and on elevation, whereas Glasgow (55°51'N, 04°12'W, 0-100m amsl) has a mild temperate climate type, due to strong maritime influences. Indeed, a comparison of climate normals for both locations shows that winter conditions in Curitiba are comparable to those found in summer in Glasgow (Figure 2).

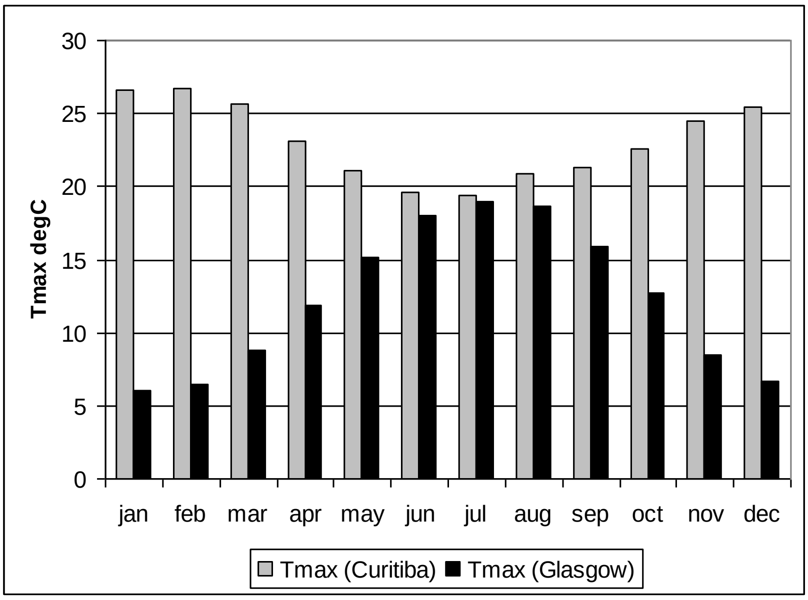

Figure 2: Monthly averages over 1961-1990 of maximum temperatures (Tmax) for Curitiba (http://www.inmet.gov.br) and Glasgow (http://www.metoffice.gov.uk), respectively.

Personal data were based on answers to a thermal comfort questionnaire, designed from recommendations of ISO 10551 (ISO 10551, 1995). The first part of the questionnaire consists of items related to gender, age, height, weight, clothing (in Curitiba, individual clothing was composed from clothing units (provided in ISO 9920) obtained from questioning the respondents in this regard, which were later added to a single clo-value; in Glasgow, a look-up table was used based on Annex A of ISO 9920 for estimating the respondent's overall clo-value), time of residency (to account for the acclimatisation effect) and time spent outdoors in minutes before completing the survey. The second part of the questionnaire deals with items related to thermal perception and preference. We used for both (perception and preference) the symmetrical 7-point two-pole scale ranging from -3='cold' or 'much cooler' over 0='neutral' to +3='hot' or 'much warmer'.

Following the recommendations of ASHRAE Standard 55 (ASHRAE, 2004), only data from respondents who had spent at least 15 minutes in the outdoor space entered the analysis. Thus, in Curitiba, the resulting sample consists of 1654 thermal sensation votes (out of a total of 2024 responses). In Glasgow, the sample was significantly smaller: 567 thermal sensation votes (from a total of 763 responses). It should be stressed that the population size of Curitiba is about 3.2 Million people, whereas Glasgow has presently around 600,000 inhabitants.

UTCI Calculations

Values of the UTCI equivalent temperature were obtained for the Curitiba sample by running the UTCI-Fiala model coupled with the UTCI clothing model for the monitored climatic conditions, and by subsequently computing the strain index and comparing it to the reference conditions. UTCI values were also obtained by the simplified regression approach provided by the operational procedure (Bröde et al. 2011). As the values from both procedures for the Curitiba sample were highly correlated (r>0.99) and showed negligible bias (-0.08 K) and root-mean-squared differences (0.39 K), only the simplified regression approach was applied for the Glasgow sample. As UTCI requires the input of wind speed at 10 m above the ground, the wind speed values measured at 2.1 m and 1.5 m above ground (in Curitiba and in Glasgow, respectively) were scaled-up according a logarithmic formula as proposed by the operational procedure (Bröde et al., 2011a).

Data Analysis and Statistics

To consider the potentially non-linear average course of clothing thermal insulation and thermal sensation related to ambient temperature and UTCI, respectively, general additive models with locally estimated smoothing functions (LOESS) and 95%-confidence bands were computed separately for the samples of Curitiba and Glasgow.

The observed thermal sensation votes were compared to the dynamic thermal sensation (DTS) predicted by the UTCI-Fiala model (Fiala et al., 2011). The goodness-of-fit for the two samples, for the whole data and for the different subgroups characterised by age, gender and body-mass-index was assessed by the averaged error (bias), with the error calculated as the difference of the predicted minus the observed values, by the root mean squared error (RMSE) and by the Pearson correlation coefficient (rp) between observed and predicted values.

Results and Comparisons

Figures 3-5 show comparisons between observed clothing levels (predicted by UTCI's clothing model versus actual garments observed) and votes of thermal sensation, in relation to ambient temperature variations and to UTCI values. With regard to observed and predicted clothing insulation (Figure 3), mean values with 95% confidence bands were obtained from fitting locally estimated smoothing splines (LOESS) to observed clothing. For comparison, the values applied by the UTCI-clothing model (Havenith et al., 2011) are also shown. Figure 4 shows thermal sensation votes related to air temperature for both samples in terms of mean values with 95% confidence bands obtained from LOESS curves. Figure 5 presents thermal sensation votes related to UTCI for both samples, again from LOESS means, where the dynamic thermal sensations (DTS) predicted by the UTCI-Fiala model for the reference conditions are also included: for short term (0.5 h), steady-state (2 h) and averaged (0.5, 1, 1.5, 2 h) exposure times (cf. Table 1).

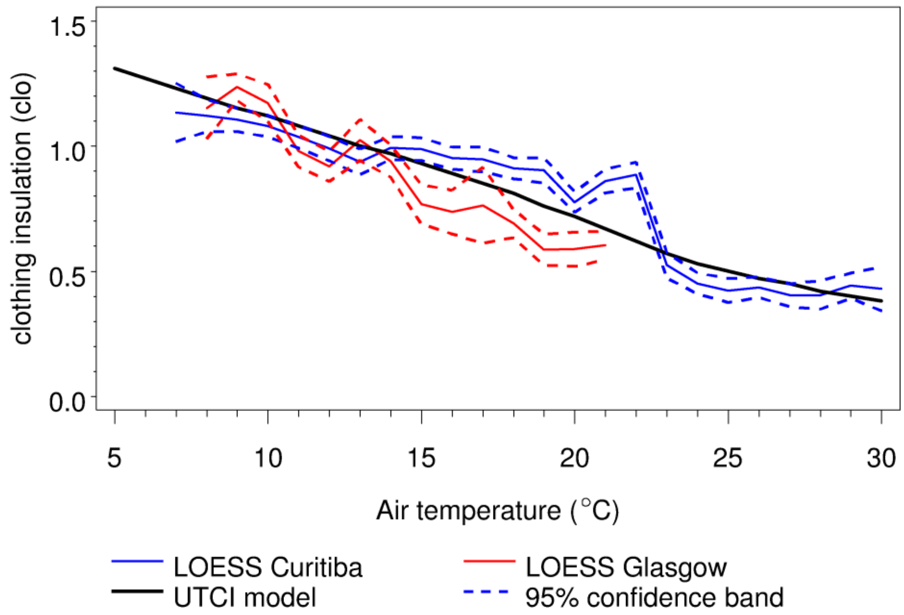

Figure 3: Clothing thermal insulation related to air temperature for the samples from Curitiba and Glasgow against predicted (UTCI) clothing insulation

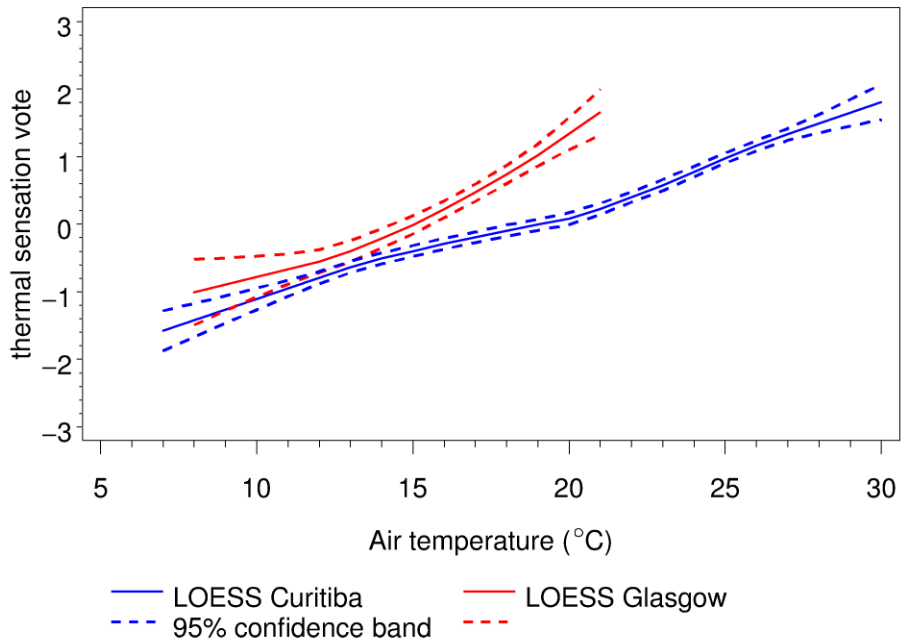

Figure 4: Thermal sensation votes related to air temperature for the samples from Curitiba and Glasgow

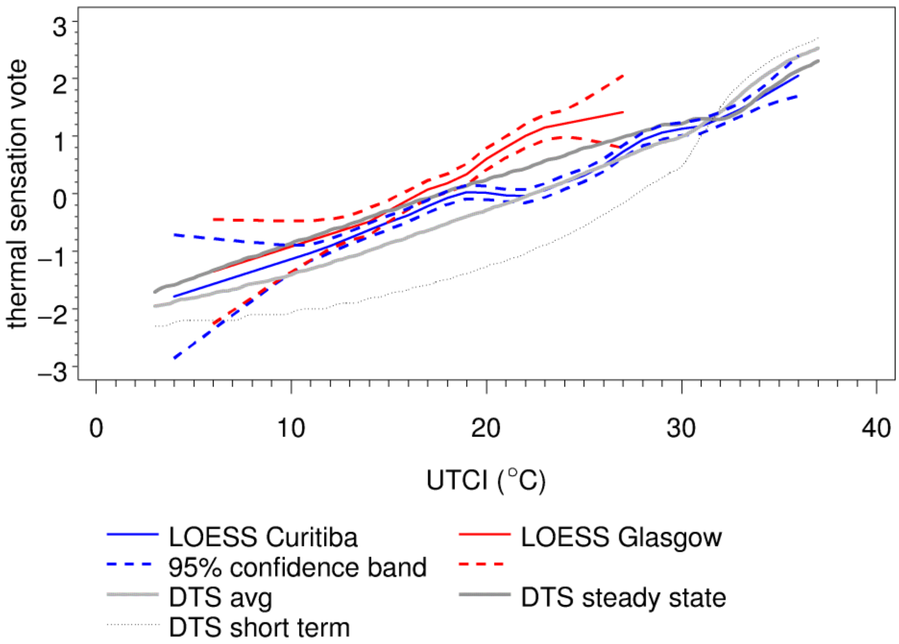

Figure 5: Thermal sensation votes related to UTCI for the samples from Curitiba and Glasgow compared to the predicted dynamic thermal sensations (DTS) for short term (0.5 h), steady-state (2 h) and averaged (avg) over 0.5, 1, 1.5, 2 h exposure times

Results suggest that clothing levels are fairly well predicted by UTCI's clothing model for low temperatures in both cases and for higher temperatures in Curitiba. A small offset was noticed for Glasgow from the onset of the summer period, with UTCI overestimating actual clothing. More notable however were differences between clothing levels for Curitiba and Glasgow for a same ambient temperature range (roughly 15-20 °C), which is also reflected on the thermal sensation votes for both locations. The same deviation in terms of thermal perception votes is noted in Figure 4, starting at about 15 ºC. As those divergences are found for the start of the summer period in Glasgow, it is suggested that people under those climatic conditions accept lower air temperatures and indeed regard those as comfortable presumably due to acclimatization effects.

For calculated UTCI, similar discrepancies have been observed for both cases, with a slight overestimation of actual thermal sensation for Curitiba and a slight underestimation of actual thermal sensation for Glasgow for UTCI steady-state results (2 h, Figure 5).

Table 1 presents the error analysis of the dynamic thermal sensation (DTS) predicted by the UTCI-Fiala model in relation to location (city) and simulated outdoor exposure time. In general, results in Table 1 show that biases and RMSE between observed and predicted thermal sensation votes were smaller and Pearson correlation coefficients were higher for the Curitiba sample, which may have been affected by the sample size. Though the predictions averaged over the 2 h exposure times performed slightly better for the Curitiba sample, results for the Glasgow population and the whole sample are better for steady state UTCI predictions (2 h), which conforms to observations made above with regard to Figure 5.

Table 1: Number of observations (n), averaged errors (bias), root mean squared errors (RMSE) and Pearson correlation coefficients (rp) of the observed thermal sensation votes compared to the dynamic thermal sensation predicted by the UTCI-Fiala model for the reference conditions. Results in relation to location (city) were obtained from short term (0.5 h) and steady state predictions (2 h), as well as from predictions averaged over simulated exposure times of 0.5, 1, 1.5, 2 h

City	*Exposure Time*	*n*	*bias*	*RMSE*	*rp*
Curitiba	*short term*	1654	-0.85	1.36	0.60
	steady state	1654	0.25	0.97	0.61
	Averaged	1654	-0.13	0.95	0.62
Glasgow	*short term*	567	-1.67	2.09	0.43
	steady state	567	-0.22	1.26	0.45
	Averaged	567	-0.75	1.45	0.45
Total	*short term*	2221	-1.06	1.58	0.51
	steady state	2221	0.13	1.05	0.53
	Averaged	2221	-0.29	1.10	0.53

As discussed earlier for the Curitiba sample (Bröde et al., 2011b), the short-term predictions of thermal sensation were inferior to the predictions after 2 h or averaged over 2 h of exposure time in both cases. The reason for the discrepancies appears to arise from the way exposures were simulated. In UTCI as well as in this study, the simulations were conducted assuming instant exposures to the outdoor climate conditions. Sudden exposures (of unclothed thermo-neutral subjects) to cool/cold conditions are typically associated by a *cold sensation 'overshoot'*. In real life such conditions may be experienced e.g. when taking a cold shower where, initially, there is a sensation of extreme cold but followed by an 'adaptation' towards more moderate feelings as time progresses. This dynamic 'overshoot' effect is simulated by the UTCI-Fiala model taking into account temporal changes of skin temperature as additional signals from cutaneous thermoreceptors (Fiala et al., 2011). As indicated by the dashed line of DTS 'short term' in Figures 5 this resulted in underpredicting thermal sensations in the initial phases of the outdoor exposures.

In the field surveys analysed, however, the transition from indoors to outdoors may not have been instant and also clothing might have played a stronger mitigating role resulting in a less pronounced initial transient skin cooling than simulated. In future studies research might thus focus on the investigation of the role and relevance of initial conditions on UTCI and predicted responses of subjects exposed to outdoor climate conditions. Further aspects to consider in future studies might include the impact of expectations and experience of the outdoor climate prior to the actually considered period (Knez et al., 2009; Nikolopoulou & Steemers, 2003), which could also be associated with the local building characteristics usually with low thermal insulation, lack of air conditioning with enclosed semi-outdoor spaces resembling outdoor conditions (Spagnolo & de Dear, 2003). Specifically for Glasgow, there is also the possibility that the outcome might be to some extent to greater deviations observed in clothing insulation from the UTCI model. Future studies can also investigate specifically the role of clothing insulation on thermal sensation as an additional input to the UTCI-Fiala model, as was done for the Curitiba data (Bröde et al., 2011b), but with insulation values adapted for the Glasgow sample.

As identical UTCI values should represent equal physiological strain (Jendritzky et al., 2011) one would expect smaller deviations in thermal sensation between Curitiba and Glasgow samples on a UTCI scale. This seems to be confirmed partly by Figure 5, however higher divergences between samples and deviations from steady-state UTCI predictions occur at approximately 18 ºC UTCI onwards. This approximately compares to the temperature range with the greatest deviations in clothing insulation observed in both locations.

Table 2 shows the results considering personal characteristics (gender, age and body-mass), but restricting to steady-state (i.e. after 2 h) exposure times, which showed the best overall fit in Table 1. The group analysis (Table 2) took into account classifications from the World Health Organisation (WHO, 1995; WHO expert consultation, 2004) for age [under 25 years-old 'young', between 25 and 64 'adult' and above 64 'elderly'] and for the body mass index (BMI), calculated as BMI=weight/(0.01×height) [BMI groups categorised as 'underweight' for BMI<18.5 kg/m2, 'normal' for 18.5≤BMI<25 kg/m2, 'overweight' for 25≤BMI<30 kg/m2 and 'obese' for BMI>30 kg/m2]. A strong similarity is observed for both samples with a concentration of respondents being adults (about 60% of the sample in both locations), BMI normal to obese (over 80% in both cases) and male (around 60% of the respondents).

Table 2: Number of observations (n), averaged errors (bias), root mean squared errors (RMSE) and Pearson correlation coefficients (rp) of the observed thermal sensation votes compared to the dynamic thermal sensation predicted by the UTCI-Fiala model for the reference conditions. Results in relation to location (city), age, BMI and gender were obtained from steady state predictions (2 h), giving the least overall bias and RMSE (cf. Table 1)

City			*n*	*bias*	*RMSE*	*rp*
Curitiba	*Age group*	*young*	494	0.12	0.98	0.65
		adult	1008	0.29	0.96	0.60
		elderly	152	0.34	0.97	0.51
	BMI group	*underweight*	42	0.30	0.98	0.63
		normal	897	0.27	0.97	0.63
		overweight	528	0.24	0.96	0.59
		obese	187	0.15	0.97	0.60
	Gender	*female*	710	0.24	1.05	0.60
		male	944	0.25	0.90	0.62

City			n	bias	RMSE	rp
Glasgow	Age group	young	142	-0.24	1.29	0.44
		adult	333	-0.20	1.22	0.43
		elderly	92	-0.27	1.38	0.50
	BMI group	underweight	15	-0.09	1.35	0.66
		normal	283	-0.15	1.25	0.49
		overweight	188	-0.26	1.25	0.40
		obese	81	-0.40	1.33	0.31
	Gender	female	220	-0.16	1.30	0.48
		male	347	-0.26	1.24	0.43

As mentioned before, UTCI predictions after 2-h exposure overestimated thermal sensation for Curitiba and underestimated it for the Glasgow sample. Taking this into account, the overall bias was consistent for all subgroups under both climatic conditions. The analyses of the subgroups revealed a negligible influence of gender and age on the prediction error, whereas there was a noticeable increase in the error for obese relative to underweight persons for Glasgow. Within the conditions studied here, UTCI appears to be applicable to males and females, to young and adult people as well as to the elderly. The small RMSE of less than 1 point on the 7-point thermal sensation scale observed in all subgroups for Curitiba (and just over 1.3 for Glasgow) suggests a reasonable goodness-of-fit in both cases. It should be stressed, however, that a clear understanding of the subgroup effect such as the impact of age and BMI on thermal sensation or on the error of UTCI prediction is not feasible, as the sample size varies substantially for each subgroup.

Concluding Remarks

In general, UTCI predictions of thermal sensation from measured microclimatic data showed a good agreement with observed votes computed for ‘steady-state’ conditions (after 2-h exposure) in both samples, even though averaging over exposure time yielded improved predictions in Curitiba. Observed clothing levels were fairly well predicted by UTCI’s clothing model for both locations, with a small offset (overestimation) for Glasgow from the onset of the summer period. When considered in relation to UTCI, divergences to the two samples’ thermal responses were lower than for the ambient temperature with a good match to predicted data after 2-h exposure until about 18 ºC UTCI. It is suggested that the differences noticed further on are linked to deviations in clothing insulation observed in both locations advocating for more elaborate simulations and analyses.

Interestingly, respondents in Glasgow wore much less insulating clothing than the participants in Curitiba at identical air temperatures. A similar effect had been observed for the Curitiba sample (Bröde et al., 2011b) showing that, for a smaller range of 20-22 °C ambient temperature, respondents wore more insulating clothing during the cold season than during summertime. In a previous analysis (Bröde et al., 2011b), the introduction of the observed clothing insulation as additional input parameter to the UTCI-Fiala model did not improve the predictions of thermal sensation, suggesting a good agreement of the averaged observed insulation with the presumed UTCI-clothing model (Havenith et al., 2011). Whether such an extended simulation would be beneficial to the Glasgow sample with greater deviations from the UTCI-clothing model has to be answered by still ongoing analyses.

Acknowledgements

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