Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Residual analysis of UTCI predictions on outdoor thermal sensation survey data

Peter Bröde[1], Eduardo L. Krüger[2] and Dusan Fiala[3]

1 IfADo – Leibniz Research Centre for Working Environment and Human Factors, Dortmund, Germany, correspondence e-mail broede@ifado.de;
2 Technological University of Parana, Curitiba, ekruger@utfpr.edu.br;
3 ErgonSim — Comfort Energy Efficiency, Stuttgart, Germany, dfiala@ergonsim.de

Abstract

The Universal Thermal Climate Index UTCI assesses the interaction of ambient temperature, wind, humidity and radiant fluxes on human physiology in outdoor environments on an equivalent temperature scale. It is based on the UTCI-Fiala model of human thermoregulation and thus also allows for thermal comfort prediction. Comparing UTCI predictions to thermal sensation votes recorded on the 7-unit ASHRAE scale in outdoor comfort surveys with 1685 respondents in Curitiba and 567 in Glasgow, respectively, yielded negligible bias and less than one unit root-mean squared error (rmse) for Curitiba, but a noticeable underestimation of actual thermal sensation votes (bias=-0.73) with increased rmse=1.44 in Glasgow. Residual analyses revealed that the factors age, gender, body composition, site morphology (open space, street canyon), climatic state (comfort/discomfort) and clothing behaviour only explained a small portion of the error variance, which was dominated to over 95% by residual inter-individual variability. Adding historical weather information from the previous day to the Glasgow data gave superior information compared to longer time lags and helped to reduce the residual variance to 89%. Those numbers underpin current limitations in individual thermal comfort prediction, while UTCI performance appears reasonable at the population level.

Keywords: thermal comfort, outdoor environment, survey, model, error analysis

1 Introduction

The Universal Thermal Climate Index UTCI aims for the assessment of the outdoor thermal environment in the major fields of human biometeorology (Jendritzky et al., 2012). UTCI summarises the interaction of ambient temperature, wind, humidity and radiant fluxes on human physiology. The dynamic physiological responses are simulated by an advanced multi-node model of human thermoregulation (Fiala et al., 2012) coupled with a model of adaptive clothing choice in urban populations (Havenith et al., 2012), which also considers the distribution of the clothing over different body parts, and 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 (1.1 m/s) on the level. UTCI values are presented on an equivalent temperature scale. 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.

The operational procedure provides simplified algorithms for computing UTCI values from air temperature, wind speed, mean radiant temperature and water vapour pressure and was completed by an assessment scale establishing UTCI threshold values that define different categories of thermal stress from extreme cold to extreme heat, with UTCI values from 18 to 26 °C complying to the thermal comfort zone (Bröde et al., 2012a).

We have already presented the UTCI operational procedure (Bröde et al., 2010) and its application to outdoor thermal comfort surveys from Curitiba, Brazil, and Glasgow, UK (Krüger et al., 2012) at previous Windsor Conferences. For the interviews carried out in Curitiba, the observed clothing insulation was in good agreement with the UTCI-clothing model. Also the actual thermal sensation votes were well predicted by the UTCI-Fiala model simulations for UTCI reference conditions with negligible averaged error (bias) and less than one unit root-mean squared errors (rmse) on the 7-unit thermal sensation scale (ISO 10551, 1995). Detailed simulations considering the individual climatic and clothing conditions did not further improve the predictions indicating the validity of the assumptions underlying the UTCI model for the surveys in Curitiba (Bröde et al., 2012b).

However, we had observed larger negative bias (i.e. underestimation) and rmse for the thermal sensation votes from Glasgow in connection with less clothing insulation worn than assumed by the UTCI model. Therefore, with focus on the Glasgow survey in this paper,

- we analyse how the residues of UTCI predictions on thermal sensation depend on personal characteristics (gender, age, body composition) and urban site morphology (open spaces vs. street canyons);
- we study the influence of clothing choice on the residues by detailed simulations with the UTCI-Fiala model; and
- we study experience related effects on thermal sensation (Nikolopoulou et al., 2001; Nikolopoulou & Steemers, 2003) by adding meteorological data and UTCI values recorded days, weeks and months before each survey to the data base.

2 Materials and Methods

Here, we briefly review the field surveys' methodology, as detailed descriptions have already been given elsewhere (Bröde et al., 2012b; Krüger et al., 2012).

2.1 Outdoor surveys

Field measurements with concurrent administration of comfort questionnaires were carried out in Curitiba, Brazil (25°26'S, 49°16'W, 917m amsl, subtropical climate in elevation) and in Glasgow, UK (55°51'N, 04°12'W, 0-100m amsl, maritime temperate climate). The same team leader directed both field studies, thus ensuring compatibility of the employed procedures. In both locations, surveys were carried out in pedestrian areas during daytime (typically from 10am to 3pm local time) with portable weather stations recording air temperature, relative humidity, air velocity and globe temperature, from which mean radiant temperature was calculated (ISO 7726, 1998).

We applied a standard comfort questionnaire to collect personal information like age, gender, height and weight. Participants rated their thermal sensations using a symmetrical 7-unit two-pole scale ranging from -3='cold' over 0='neutral' to +3='hot' (ISO 10551, 1995) and intrinsic clothing thermal insulation was determined from the worn items according to standardised tables (ISO 9920, 2007).

2.2 Data analysis and statistics

Only data of permanent residents (i.e. living for more than 6 months in the city) who had spent at least 15 min outdoors before the interview were considered eligible, thus 567 responses from Glasgow and 1685 from Curitiba were included in the analysis.

UTCI values were computed from measured air temperature, humidity, air velocity and mean radiant temperature and predictions of dynamic thermal sensations (DTS) averaged over 2 h exposure time were obtained from the output of the UTCI-Fiala model (Bröde et al., 2012a; Fiala et al., 2012). Prediction error was defined as the difference of DTS to the actual thermal sensation vote, with negative values indicating underestimation and positive values representing overestimation. We calculated the averaged error (bias), root-mean squared error (rmse) and Pearson's correlation coefficient (rp) to asses the deviations between predicted and measured thermal sensation votes.

General additive models with locally estimated smoothing functions (LOESS) and 95%-confidence intervals (CI) were computed to describe the average course of clothing insulation, of thermal sensation and of the prediction error considering the potentially non-linear relationships with air temperature and UTCI, respectively. For comparing models with different predictors, Akaike's Information Criterion (AIC) was used to asses the goodness-of-fit (Zuur et al., 2009).

The influence of potential modifiers on the prediction error was assessed by computing bias, rmse and correlation coefficients for subgroups defined by city, gender and other classifying factors as described below. We calculated body mass index (BMI) from weight and height and classified the persons' body composition as 'underweight', 'normal', 'overweight' or 'obese' (Bröde et al., 2012b; WHO, 1995) according to WHO guidelines, which were also applied to build age subgroups as below 25 years (young), between 25 and 64 (adult) and above 64 (elderly). Two urban site morphology groups were defined: 'street canyons', where most of the surveys took place in both samples, and 'open spaces or crossroads'. We used the thermal state classification provided by UTCI with the thermal comfort zone corresponding to UTCI values from 18 to 26 °C, cold discomfort below 18 °C and warm discomfort above 26 °C (Bröde et al., 2012a). The deviation of worn clothing insulation (Icl_{obs}) from the UTCI-clothing model (Icl_{mod}) was determined and percentage deviation was calculated as $(Icl_{obs}-Icl_{mod})/Icl_{mod}*100$. Percentage deviation was classified in three levels as more than 20% below (<-20% UTCI) or above (>+20% UTCI) or within ±20% of UTCI clothing insulation.

Variance components of prediction error attributable to the above random factors were obtained separately for both cities and for the total sample, respectively, by mixed model ANOVA using SAS® Version 9.2 (Littell et al., 1996).

Historical weather records for time periods preceding the Glasgow campaigns were obtained from Weather Underground (www.wunderground.com) for the weather station East Renfrewshire (IGLASGOW1, 55.78 °N, 4.42 °W) and comprised records in five minute intervals of air temperature, wind speed, relative humidity and solar radiation. Mean radiant temperature was estimated for these records using the RayMan software (Matzarakis et al., 2010). This information was then used to calculate UTCI values and from the recordings obtained between 10am and 3pm (corresponding to the period of interviewing) daily averages were calculated. So we obtained averaged historical UTCI values 1, 3, 7, 14, 28 and 56 days prior to the actual campaign thus covering in a logarithmic manner periods from days, weeks to almost two months. The differences of actual to historical UTCI were used as predictors of the residual prediction error of thermal sensation by fitting LOESS models. For the variance component analysis, these differences were classified in intervals ±2.5 °C (actually as cool/warm as in previous period), <-2.5 °C (actually cooler than in previous period), >+2.5 ° (actually warmer), with the thresholds corresponding to the inter-quartile range for 1 day lagged values.

3 Results and Discussion

Clothing thermal insulation showed considerable inter-individual variation, but on average decreased with increasing air temperature in both study areas (Fig. 1A). It was in good agreement with the UTCI-clothing model, especially at high temperatures in Curitiba and at lower temperatures in both cities. However, greater differences between cities were observed from 18 to 22 °C with people in Glasgow consistently wearing lower insulating clothing at identical temperatures than in Curitiba. Overall we observed mean deviations (percentage deviations) from the UTCI-clothing model of 0.02 clo (2%) in Curitiba and -0.10 clo (-12%) in Glasgow. Thermal sensations also varied largely and increased with temperature as well as with UTCI (Fig. 1B). They were higher in Glasgow compared to Curitiba, especially in the temperature range which corresponded to the larger deviations in clothing insulation.

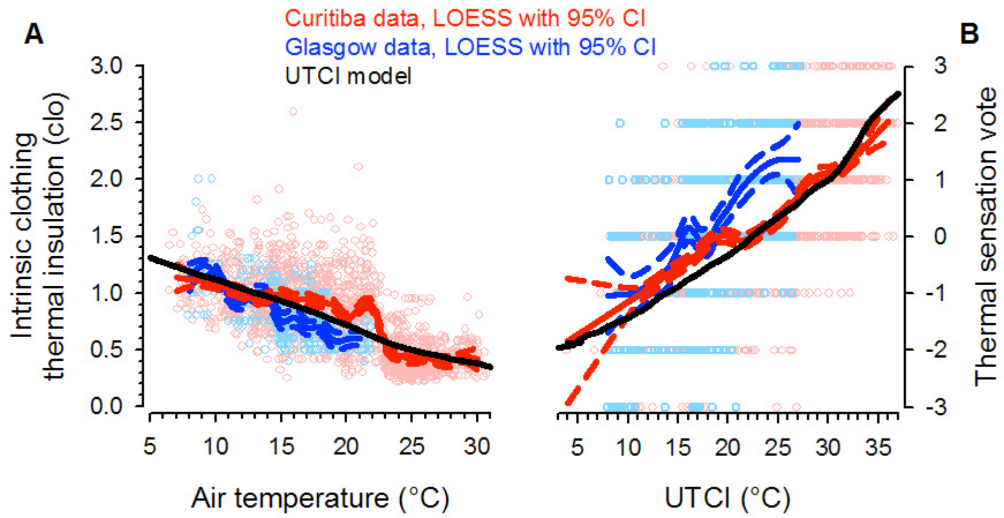

Figure 1. Individual recordings in Glasgow (blue) and Curitiba (red) superimposed by locally estimated smoothing splines (LOESS) with 95% confidence intervals (CI) for (A) clothing thermal insulation related to air temperature and (B) thermal sensation votes (-3:'cold',…,0:'neutral',…,+3:'hot') related to UTCI. Black lines indicate predictions by the UTCI clothing model (A) and by the UTCI-Fiala model for reference climatic conditions (B)

3.1 Prediction error and model complexity

Table 1 compares the prediction errors in thermal sensation for both cities and the whole sample calculated for UTCI reference environmental conditions, for actual meteorological input data, and additional for actual meteorological data also considering the worn clothing insulation. Generally, bias was negligible and rmse was less than one unit on the 7-unit thermal sensation scale for Curitiba, whereas thermal sensations were noticeably underestimated (bias < -0.7) with greater rmse in Glasgow. However, in all locations the prediction for the reference environment performed as well as those for actual weather data. This is in line with the requirements formulated for UTCI and other thermo-physiological indices, that identical index values represent the same physiological strain (Jendritzky et al., 2012).

Table 1. Averaged errors (bias), root-mean-squared errors (rmse) and Pearson correlation coefficient (rp) by study area between the observed thermal sensation and the dynamic thermal sensation predicted by the UTCI-Fiala model for the UTCI reference environment (REF), for actual climatic conditions (ACTUAL) and for actual climate with individually recorded clothing insulation (INDIV clo).

Model	**Curitiba** (n=1685)			**Glasgow** (n=567)			**Total** (n=2252)		
	bias	*rmse*	*rp*	*bias*	*rmse*	*rp*	*bias*	*rmse*	*rp*
REF	-0.13	0.96	0.62	-0.73	1.44	0.46	-0.28	1.10	0.54
ACTUAL	-0.15	0.95	0.63	-0.78	1.47	0.46	-0.31	1.10	0.54
INDIV clo	-0.18	1.05	0.56	-1.03	1.67	0.33	-0.39	1.24	0.46

Interestingly, Table 1 also indicates that using a more complex model which also incorporated actual clothing insulation yielded deteriorated predictions. As a consequence from these results, we restricted our subsequent analyses on the predictions for UTCI reference conditions.

3.2 Factors influencing the prediction error

There were only small changes in bias, rmse and correlation presented for the different subgroups in Table 2 compared to the overall results (Table 1). Although the BMI categories showed a tendency of increased underestimation error with increasing obesity, the variance component analysis (Fig. 2) revealed that all factors and their interactions accounted only for a very small portion of total variance, which was dominated to more than 95% by residual inter-individual variability.

Only the discrepancy between Glasgow and Curitiba showed up as a significant contribution of “city” in the results for the total sample, thus corresponding to other surveys with e.g. higher neutral temperatures observed in Greece compared to the UK or Germany (Nikolopoulou & Lykoudis, 2006).

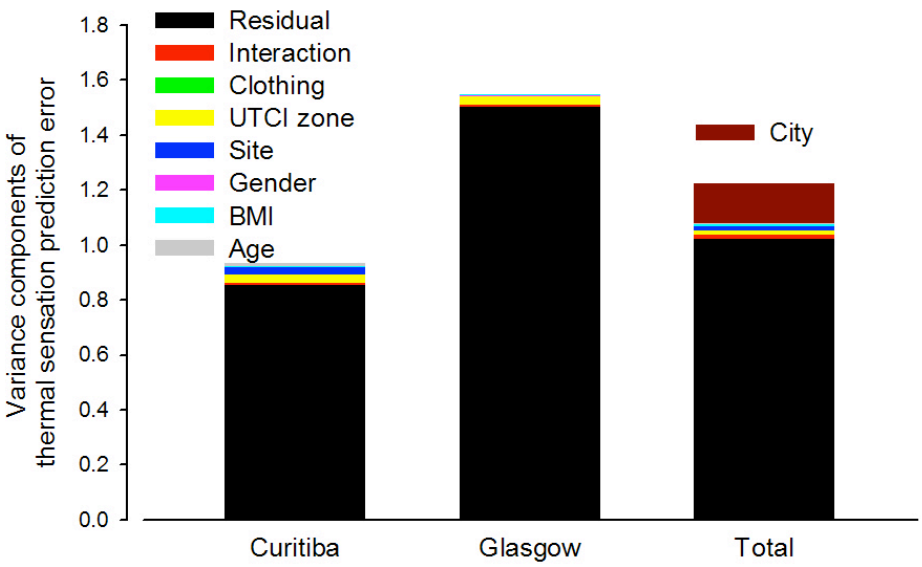

Figure 2. Partitioning of the variance for the error in thermal sensations predicted by the UTCI model into factors corresponding to Table 2 shown separately for the two study locations and the total sample. Note that factor “city” only applies to the total sample and that the contributions of all interactions are summated into a single term

Table 2. Averaged errors (bias), root-mean-squared errors (rmse) and Pearson correlation coefficient (rp) by study area between the observed thermal sensation votes and the dynamic thermal sensation predicted by the UTCI-Fiala model for UTCI reference environment (REF) in relation to the modifying factors age, body composition (BMI), gender, site morphology, thermal comfort/discomfort zone according to UTCI and deviation of worn clothing insulation from the UTCI model (Actual clo).

Factor	**Curitiba**				**Glasgow**				**Total**			
	n	*bias*	*rmse*	*rp*	*n*	*bias*	*rmse*	*rp*	*n*	*bias*	*rmse*	*rp*
Age												
young	501	-0.24	0.98	0.66	142	-0.73	1.43	0.48	643	-0.35	1.10	0.60
adult	1032	-0.09	0.94	0.61	333	-0.73	1.41	0.43	1365	-0.24	1.08	0.53
elderly	152	-0.10	0.96	0.50	92	-0.77	1.54	0.54	244	-0.35	1.21	0.41
BMI												
underweight	44	0.00	0.91	0.69	16	-0.48	1.47	0.74	60	-0.13	1.09	0.64
normal	912	-0.10	0.94	0.64	283	-0.67	1.39	0.51	1195	-0.24	1.07	0.57
overweight	537	-0.17	0.97	0.59	189	-0.77	1.44	0.40	726	-0.32	1.12	0.50
obese	192	-0.21	0.99	0.62	79	-0.93	1.57	0.34	271	-0.42	1.19	0.50
Gender												
female	718	-0.12	1.01	0.63	222	-0.65	1.46	0.46	940	-0.25	1.13	0.56
male	967	-0.14	0.91	0.62	345	-0.79	1.43	0.47	1312	-0.31	1.07	0.53
Site morphology												
Crossroads & Open Spaces	580	0.03	0.98	0.68	197	-0.76	1.53	0.35	777	-0.17	1.14	0.56
Street Canyon	1105	-0.22	0.95	0.59	370	-0.72	1.38	0.52	1475	-0.34	1.07	0.53
UTCI zone												
cold disc.	492	-0.31	1.00	0.32	292	-0.60	1.47	0.26	784	-0.42	1.20	0.31
comfort	624	-0.12	0.89	0.15	261	-0.89	1.40	0.38	885	-0.35	1.07	0.17
warm disc.	569	0.02	0.99	0.36	14	-0.60	1.41	0.42	583	0.00	1.00	0.34
Actual clo												
<-20% UTCI	454	-0.16	0.98	0.58	207	-0.70	1.43	0.44	661	-0.33	1.14	0.50
±20% UTCI	806	-0.10	0.94	0.67	327	-0.78	1.46	0.44	1133	-0.30	1.12	0.56
>+20% UTCI	425	-0.15	0.96	0.53	33	-0.53	1.22	0.79	458	-0.18	0.98	0.54

3.3 Prediction error and historical weather data in Glasgow

Figure 3A illustrates the influence of changes in UTCI compared to prior values with different time lags on thermal sensation prediction error for the survey data from Glasgow. The LOESS functions for greater lags (3 to 56 days) oscillated around the mean bias indicating a limited predictive value. On the other hand, the information from the previous day (lag 1 day) showed a more systematic variation with a reduced underestimation at positive differences, meaning that a cooler day before resulted in less warm sensations of the respondents and thus in smaller negative bias.

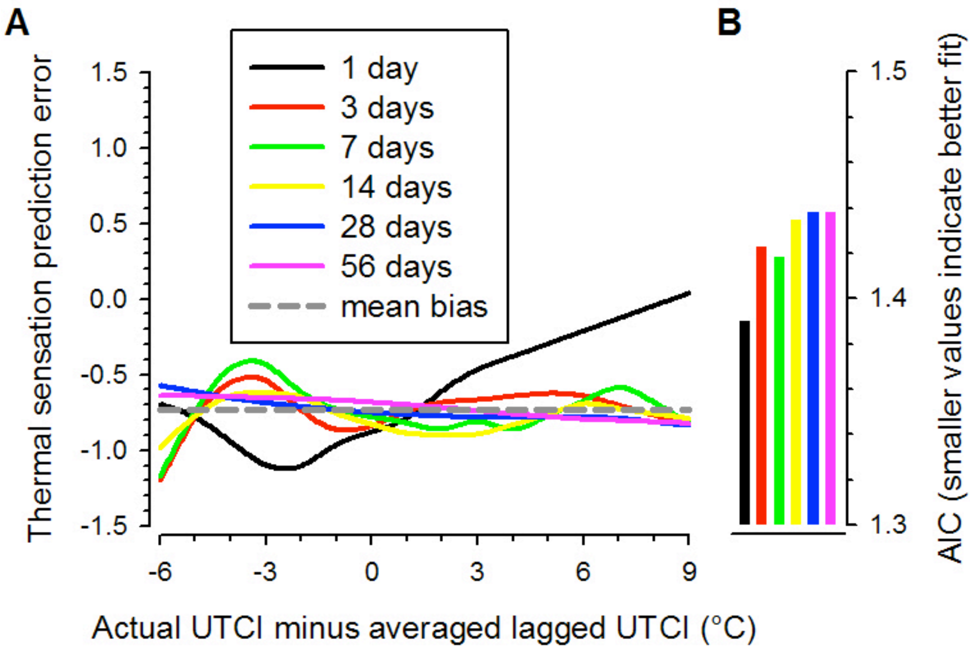

Figure 3. (A): LOESS smoothing functions of the prediction error in thermal sensation related to the difference of actual UTCI to past values averaged over different time lags. The dashed grey line indicates the average bias for the Glasgow data. (B): Akaike's Information Criterion (AIC) for the LOESS functions in (A) with smaller values indicating a superior goodness-of-fit.

The AIC values (Fig. 3B) indicate that 1 day lag information fitted better than longer lag periods. This concurs with regression analyses from earlier studies (Nikolopoulou et al., 2001) showing lower capacity of temperatures recorded at longer time lags for neutral temperature prediction.

Figure 4 presents the prediction error variance components for Glasgow in relative terms pointing out that the consideration of UTCI values from the previous day, in interaction with the other factors, reduced the residual inter-individual variability from over 95% to 89%.

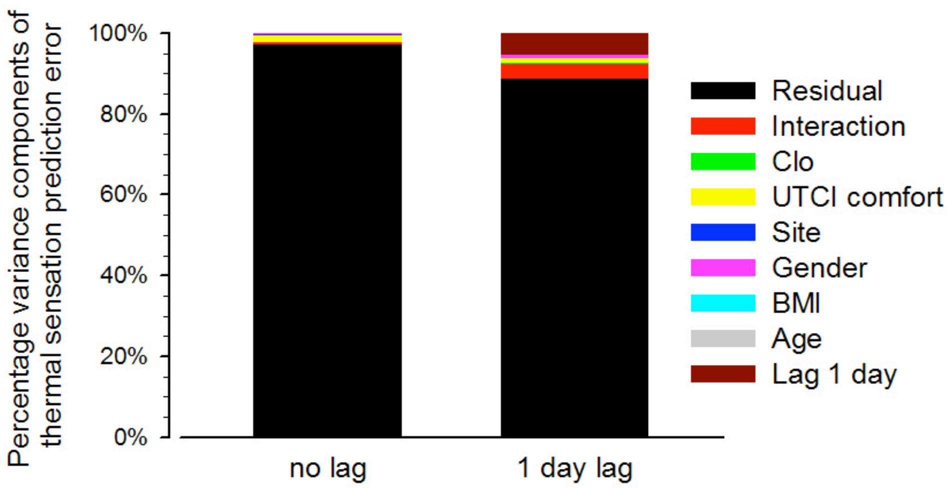

Figure 4. Relative partitioning of the error variance for thermal sensations predicted by the UTCI model for the Glasgow data into factors corresponding to Table 2 (left bar, cf. Fig. 2) and after incorporating the change to UTCI from the previous day (Lag 1 day). Note that factor "Lag" only applies to the right bar and that the contributions of all interactions are summated into a single term.

4 Conclusions

The dynamic thermal sensations calculated by the UTCI-Fiala model for UTCI reference climatic conditions provided predictions of actual thermal sensation votes recorded in outdoor field surveys with an rmse of about 1 unit on the 7-unit thermal sensation scale. Given that thermal sensation votes in the range of ±1 are applied to define thermal comfort in survey studies (Rossi et al., 2012), this level of accuracy appears reasonable. The prediction error was largely independent of gender, age, body composition, site morphology, thermal status, clothing choice, but thermal sensations in Glasgow were noticeably underestimated compared to Curitiba.

Additional information on prior weather as a surrogate of short-term experience (Nikolopoulou & Steemers, 2003) could only help reducing this bias if it referred to a previous cooler day. It was interesting to note, that explicitly considering individual clothing behaviour in the heat exchange model did not improve the predictions. This might be explainable by inter-individual differences in human thermoregulation which might be interconnected with the choice of clothing.

Though the prediction may be considered acceptable at the population level, the large portion of 90% and more of unexplained inter-individual residual variance indicates current limitations in individual thermal comfort modelling and in considering regional and inter-cultural differences. Recently, attempts to adapt a thermo-physiological model to Asian populations have been made by modifying the passive part of the system, i.e. anthropometry (Zhou et al., 2013). However, given the limited influence of personal characteristics found in our study, it remains questionable, whether such alterations will sufficiently account for psychological influences (Nikolopoulou & Steemers, 2003) or even semantic differences in perceiving thermal comfort in different cultures or regions (Tochihara et al., 2012).

References

Bröde, P., Jendritzky, G., Fiala, D., Havenith, G., 2010. The Universal Thermal Climate Index UTCI in Operational Use. *Proceedings of 6th Windsor Conference: Adapting to Change: New Thinking on Comfort*, Cumberland Lodge, Windsor, UK, 9 – 11 April 2010. London: Network for Comfort and Energy Use in Buildings.

Bröde, P., Fiala, D., Blazejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., Tinz, B., Havenith, G. 2012a. Deriving the Operational Procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, 56(3), pp 481-494.

Bröde, P., Krüger, E.L., Rossi, F.A., Fiala, D. 2012b. Predicting Urban Outdoor Thermal Comfort by the Universal Thermal Climate Index UTCI - a Case Study in Southern Brazil. *International Journal of Biometeorology*, 56(3), pp 471-480.

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., Jendritzky, G. 2012. UTCI-Fiala Multi-Node Model of Human Heat Transfer and Temperature Regulation. *International Journal of Biometeorology*, 56(3), pp 429-441.

Havenith, G., Fiala, D., Blazejczyk, K., Richards, M., Bröde, P., Holmér, I., Rintamaki, H., Ben Shabat, Y., Jendritzky, G. 2012. The UTCI-Clothing Model. *International Journal of Biometeorology*, 56(3), pp 461-470.

ISO 10551, 1995. *Ergonomics of the Thermal Environment - Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales*. Geneva: International Organisation for Standardisation.

ISO 7726, 1998. *Ergonomics of the Thermal Environment - Instruments for Measuring Physical Quantities*. Geneva: International Organisation for Standardisation.

ISO 9920, 2007. *Ergonomics of the Thermal Environment - Estimation of Thermal Insulation and Water Vapour Resistance of a Clothing Ensemble*. Geneva: International Organisation for Standardisation.

Jendritzky, G., de Dear, R., Havenith, G. 2012. UTCI - Why another Thermal Index? *International Journal of Biometeorology*, 56(3), pp 421-428.

Krüger, E.L., Bröde, P., Emmanuel, R., Fiala, D., 2012. Predicting Outdoor Thermal Sensation From Two Field Studies in Curitiba, Brazil and Glasgow, UK Using the Universal Thermal Climate Index (UTCI). *Proceedings of 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World*, Cumberland Lodge, Windsor, UK, 12 – 15 April 2012. London: Network for Comfort and Energy Use in Buildings.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. *SAS® System for Mixed Models*. Cary, NC: SAS® Institute Inc.

Matzarakis, A., Rutz, F., Mayer, H. 2010. Modelling Radiation Fluxes in Simple and Complex Environments: Basics of the RayMan Model. *International Journal of Biometeorology*, 54(2), pp 131-139.

Nikolopoulou, M., Baker, N., Steemers, K. 2001. Thermal Comfort in Outdoor Urban Spaces: Understanding the Human Parameter. *Solar Energy*, 70(3), pp 227-235.

Nikolopoulou, M., Lykoudis, S. 2006. Thermal comfort in outdoor urban spaces: Analysis across different European countries. *Building and Environment*, 41(11), pp 1455-1470.

Nikolopoulou, M., Steemers, K. 2003. Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings*, 35(1), pp 95-101.

Rossi, F.A., Krüger, E.L., Bröde, P., 2012. Definição de faixas de conforto e desconforto térmico para espaços abertos em Curitiba, PR, com o índice UTCI. *Ambiente Construído* 12(1), pp. 41-59.

Tochihara, Y., Lee, J.Y., Wakabayashi, H., Wijayanto, T., Bakri, I., Parsons, K. 2012. The Use of Language to Express Thermal Sensation Suggests Heat Acclimatization by Indonesian People. *International Journal of Biometeorology*, 56(6), pp 1055-1064.

WHO 1995. *Physical status: the use and interpretation of anthropometry. Report of a WHO Expert Committee*. WHO Technical Report Series No. 854. Geneva: World Health Organisation.

Zhou, X., Lian, Z., Lan, L. 2013. An Individualized Human Thermoregulation Model for Chinese Adults. *Building and Environment*, 70, pp 257-265.

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., 2009. Things are not Always Linear; Additive Modelling. In: Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A., Smith, G.M., *Mixed effects models and extensions in ecology with R*. New York: Springer, pp 35-69.