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Empirical calibration of thermal indices in an urban outdoor Mediterranean environment

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ABSTRACT

Thermal indices are important for assessing human thermal perception and are widely used as indicators of heat strain as well as for designing, tourism and forecast purposes. This research focuses on thermal sensation scales calibration of a large number of thermal indices in order to be applied with greater success in outdoor urban environments in Mediterranean climatic zones. Field questionnaire surveys were carried out during three different seasons monitoring microclimatic variables and subjective characteristics while interviewees were asked to indicate their thermal sensation based on a seven point thermal sensation scale. Three calibration methods, linear and cubic regression as well as probit analysis, were applied and compared based on three statistical criteria. Indices' predictions according to the calibrated scales were evaluated aiming to designate the one that best simulates thermal sensation. Probit analysis calibrated indices assessment scales more adequately compared to linear or cubic regression. Overall Actual Sensation Vote (ASV), Subjective Temperature Index (STI) and Universal Thermal Climate Index (UTCI) based on the calibrated scales showed the best predictability of thermal sensation vote compared to all the indices studied.

1. Introduction

Thermal indices are models simulating human thermal perception and are widely used as indicators of the strain induced by climatic conditions [1,2] and developing health warning systems [3], for designing outdoor urban spaces [4,5] and choosing the proper materials for their construction [6], for estimating heat island effect [7], for tourism purposes [8] as well as for the forecast of biometeorological conditions [9]. They can be divided into three categories: direct, empirical and rational indices. Direct indices are based on direct measurements of environmental variables, empirical indices relate subjective thermal perception with thermal environment and rational indices are based on heat balance equation of human body [10].

Although thermal indices are in daily use for estimating outdoor thermal sensation [11], many of those were developed for indoor environments assuming still air conditions [12] and the absence of solar radiation [13], while some others were developed for outdoors conditions but can be used only in certain climates [14,15], due to adaptation or psychological factors that affect thermal perception [16]. Furthermore recent studies have shown variations between indices predictions [17] and discrepancies between predicted and actual thermal sensation [18,19].

Nowadays researchers being aware of the importance of using the appropriate index, prefer to estimate thermal sensation through thermo-physiological indices such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI), which consider the interaction of human body with its thermal environment and can be applied to the changing conditions of an outdoor environment but are more difficult to calculate compared to empirical indices such as Actual Sensation Vote (ASV) and Discomfort Index (DI). Moreover, studies have demonstrated a variation of thermal comfort thresholds in different regions [19] resulting an increased interest for the improvement of indices predictability.

In the case of the Mediterranean climate Tseliou et al. [20] examined the ability of three indices, DI, Cooling Power (CP) and PET, to describe thermal sensation while they also tried to adjust

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them based on climatic mean temperature but the improvement of indices' performance was not significant. Cohen et al. [21] applying ANOVA test and discriminate analysis calibrated PET scale while Pantavou et al. [22] using the same method with Lin and Matzarakis [23] concluded that the negative thresholds of UTCI consistent with weather measured data were lower compared to those estimated for Athens.

Moreover Pantavou et al. [24] evaluated the performance of a great number of thermal indices on quantifying thermal sensation in the area of Athens, Greece, resulting that the majority of the studied indices, simulated about 35% of thermal sensation votes. The indices that showed overall the best applicability according to the four criteria posed in the study, Subjective Temperature Index (STI) and UTCI, simulated 42.2% and 44.8% of thermal sensation votes respectively. The authors suggested that the empirical calibration of the indices is possible to provide better simulations of thermal sensation votes.

The present study aims to calibrate thermal sensation scales of a great number of thermal indices in order to improve their applicability and to be implemented more successfully in outdoor urban spaces in Athens, Greece which is considered to be a typical Mediterranean climate. Moreover, three calibration methods were compared and indices applicability, using the calibrated scales, was evaluated in order to designate the one that best simulates thermal sensation.

2. Material and methods

2.1. Field surveys

The surveys were conducted at three outdoor urban sites in Athens, Greece: Syntagma square, Ermou street and Flisvos coast, during summer, winter and a transitional season. The sites were selected based on the morphology (square, street canyon, coastal area), the function and the daily number of people visiting the place. The measurements were conducted for a total of 16 days (Table 1), two days for each site and for each season. One day during morning – midday hours and one day during afternoon – evening – night, in order to collect data for the entire day. Due to low attendance, surveys were not carried out at Flisvos coast in autumn afternoon and during winter. An additional survey was performed at Syntagma square during winter, in order to obtain a number of questionnaires closer to that collected during summer and autumn.

Air temperature (T_{air}, in °C), relative humidity (RH, in %), average wind speed (WS, in m s^{-1}), downwelling ($SR_{\downarrow}$, in W m^{-2}) and reflected ($SR_{\uparrow}$, in W m^{-2}) solar radiation, downwelling and ground total radiation ($TR_{\downarrow}$, $TR_{\uparrow}$, in W m^{-2}) on a horizontal plane as well as globe temperature (T_{globe}, in °C) were recorded at the height of 1.1 m, using a mobile meteorological station equipped with a Rotronic S_3CO_3 thermo-hygrometer supplied with a non-ventilated radiation shield of aluminum, a Second Wind C_3 anemometer, two Kipp & Zonen CM3 pyranometers one pointed towards upper and the other towards lower hemisphere, an ECO pyrgeometer and a Pt-100 thermometer in a gray ping pong ball (emissivity 0.3). Sampling was set at 30 s, except for wind speed (10 s), while the average values were stored on a CR10X Campbell Scientific data logger every minute. Ground surface temperature was measured at three points close and around the interviewees by an Infrared Thermometer.

People passing by or visiting the sites during the surveys were interviewed for about 3 min, using structured questionnaires. The structure and selection of the questions were based on previous studies [14]. The questionnaire was designed in simple and concise language while it included questions related to personal characteristics such as gender, clothing, activity during the last half hour, height and body mass, which are required for the calculation of thermal indices. Moreover the interviewees were asked to assess their thermal sensation at the moment according to ISO 10551 [25] (3, cold; 2, cool; 1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; 3, hot), named as thermal sensation vote (TSV). In total, 1706 questionnaires were completed.

Table 1
Dates and time frames of the surveys.

Season	Year	Month	Day	Time	Site
Warm	2010	July	15	16:45–19:30	Syntagma
			16	16:00–20:39	Ermou
			17	19:13–21:51	Flisvos
			18	11:33–13:50	Flisvos
			20	10:05–15:18	Syntagma
			21	10:40–14:06	Ermou
Transitional	2010	October	16	10:21–15:05	Ermou
			17	11:03–15:09	Syntagma
			20	16:15–19:30	Syntagma
			23	16:23–19:20	Ermou
			24	13:54–15:57	Flisvos
Cold	2011	February	09	15:23–19:40	Ermou
			12	11:18–15:40	Ermou
			13	11:35–14:00	Syntagma
			26	16:00–18:30	Syntagma
			27	11:59–15:00	Syntagma

2.2. Additional data and data processing

The hourly values of atmospheric pressure (P, in hPa) used for Syntagma and Ermou, comes from Thissio Station (Institute of Environment and Sustainable Development, National Observatory of Athens, NOA-IERSD) while for Flisvos comes from Hellinikon Station (Hellenic National Meteorological Service, HNMS). Data per minute of total and diffuse solar radiation were obtained by Thissio Station and were used to estimate diffuse solar radiation (DIFF, in W m^{-2}) at the measurement sites.

In order to obtain all the data needed to calculate thermal indices, downwelling and upwelling long-wave radiation on a horizontal plane ($IR_{\downarrow}$, $IR_{\uparrow}$, in W m^{-2}) were estimated using the data of $SR_{\downarrow}$, $SR_{\uparrow}$, $TR_{\downarrow}$, and $TR_{\uparrow}$. Furthermore, the following parameters were calculated: mean air temperature per season during the experimental days (T_{season}, in °C), vapor pressure (e, in hPa), mixing ratio of water vapor (w, dimensionless), wind speed at 10 m height (WS_{10m}, m s^{-1}) setting the aerodynamic roughness length at 0.01 m [26], wet bulb temperature (T_w, °C) [26], sun elevation (ELE, in degrees) [27], mean radiant temperature (T_{mrt}, in °C) derived from T_{air}, T_{globe} and WS [28], clothing insulation (I_{cl}, in clo) according to the clothing description of the respondents [29], metabolic rate (M, in W m^{-2}) by the type of respondents activity [30] and body surface (A_{du}, in m^2) based on the height and body mass of the respondents [31]. I_{cl} was not corrected by the effect of movement or wind.

Thermal indices (Table 2) were calculated by a Matlab code (MATLAB R2010a, The MathWorks Inc.) using the 3 min average of the measured parameters since that was the estimated time for completing a questionnaire.

2.3. Data analysis

Three different methods were applied in order to find the most suitable one to calibrate indices assessment scales: (1) the most common in use linear regression, (2) cubic regression which is able to simulate more accurately the observed unequal distances between the classes of thermal sensation [22] and (3) probit analysis. In the case of linear and polynomial regression, the index was used