

Article

Investigating the Behaviour of Human Thermal Indices under Divergent Atmospheric Conditions: A Sensitivity Analysis Approach

Ioannis Charalampopoulos ^{1,*} and Andre Santos Nouri ²

- 1 Laboratory of General and Agricultural Meteorology, Agricultural University of Athens, Iera Odos 75, 11855 Athens, Greece
- 2 Faculty of Architecture, University of Lisbon, Rua Sá Nogeuira, Pólo Universitário do Alto da Ajuda, 1349-063 Lisbon, Portugal; and renouri@fa.ulisboa.pt
- * Correspondence: icharalamp@aua.gr; Tel.: +30-210-529-4234

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Abstract: This paper aims to analyse and conclude about the behaviour of the most commonly used human thermal comfort indices under a variety of atmospheric conditions in order to provide further information about their appropriateness. Utilising Generalized Additive Models (GAMs), this article examines the indices' sensitivity when exposed to diverse classified atmospheric conditions. Concentrated upon analysing commonly used human thermal indices, two Statistical/Algebraic indices (Thermohygrometric Index (THI) and HUMIDEX (HUM)), and four Energy Balance Model indices (Physiologically Equivalent Temperature (PET), modified PET (mPET), Universal Thermal Climate Index (UTCI), and Perceived Temperature (PT)) were selected. The results of the study are twofold, the identification of (1) index sensitivity to parameters' variation, and change rates, resultant of different atmospheric conditions; and, (2) the overall pertinence of each of the indices for local thermal comfort evaluation. The results indicate that the thermohygrometric indices cannot follow and present the thermal conditions' variations. On the other hand, UTCI is very sensitive under low radiation condition, and PET/mPET present higher sensitivity when the weather is dominated by high radiation and air temperature. PT index provides the lower sensitive among the human energy balance indices, but this is adequately sensitive to describe the thermal comfort environment.

Keywords: human thermal comfort; bioclimatic indices; urban climate and biometeorology; generalized additive models; R-language; sensitivity analysis

1. Introduction

Within the international scientific community, aspects pertaining to outdoor human thermal conditions have grown exponentially in the past two decades. In addition, and while critical studies pertaining to climatic indices were disseminated before the turn of the century [1-13], since the ingress into the twenty-first century (and arguably further instigated by the arrival of the climate change adaptation agenda), the importance and development of climatic indices have increased. In accordance with the rational presented by Potchter et al. [14], the associated research complexity intrinsic to climatic models can be seen under two prisms, the: (i) overall review, cataloguing, structuring, and fragmentation of index typologies based upon their equational suitability and methodical pertinence [15–20]; and, (ii) the pursuit and testing of the most suitable index to estimate thermal comfort thresholds within a specific outdoor and climatic setting [21–28]. Both of these perspectives indicate the significance and opportunities regarding the correct approach to human thermal comfort thresholds within urban environments. Chronologically speaking, the increased attention upon climatic indices is likely



concomitant with the growing consensus that wholesome thermal comfort evaluations must include a combination of climatic variables, which moreover, interact with the human thermoregulatory system [9,10]. As an example, entities such as the Intergovernmental Panel on Climate Change (IPCC) have frequently disseminated reports which have described the effects of weather with a simple index based on amalgamations of air temperature (T_a) and Relative Humidity (RH). Although it is vital to recognise the value of these descriptors within the maturing climate change adaptation agenda, when considering bottom-up approaches to climatic vulnerability and influences upon human biometeorology; the exclusion of essential factors such as non-climatic variables (such as radiation fluxes) have decreased the applicability and utility for local decision making, design responses, and overall climate change adaptation efforts. Since the thermal environment directly affects human health, including psychological responses, cardiovascular functions, and human mortality [29–31], the human thermal comfort indices are an essential tool for quantitative and qualitative research regarding human wellbeing.

Thus far, a wide range of investigations have identified this specific weakness in different types of thermal comfort studies, including those that discuss the vital role of going beyond temperature variables, namely, through the crucial inclusion of radiation fluxes when approaching: (i) future modifications of thermal comfort thresholds within different climate change scenarios derived from Global Circulation Models' (GCMs) outputs [32]; (ii) overall climatic adaptation attitudes efforts within local scales in light of climate change [33–38]; (iii) thermo-physiological stress levels within different morphological canyons with different Height-to-Width ratios (H/W) and orientations [12,36,39–45]; and also, (iv) specific public realm characteristics, such as urban vegetation which, depending on their species and planting layout, can play a fundamental role in attenuating local 'in-situ', and adjacent thermo-physiological levels [12,13,46–53]. Within this article, and evocating the two discussed research prisms described by Potchter et al. [14] this study falls into the latter category, investigating the sensitivity of six selected indices under different weather conditions. More specifically, through the utilisation of Generalised Additive Models (GAMs), the sensitivity behaviour of six selected thermal comfort indices was investigated while accounting for major input variations under different classes of Wind Speed (WS) and air temperature (T_a) conditions. The disclosed sensitivity analysis further develops the methodology undertaken by Charalampopoulos [27], who launched the inaugural step in confirming the applicability of GAMs to identify the sensitivity of numerous climatic indices using high temporal resolution datasets. In this particular study, GAMs are once again utilised to approach large, yet chaotic datasets, with the aim of pinpointing the sensitivity variations between that of algebraic/statistical models against energy balance model indices under different meteorological conditions. The results of the study reinforce: (i) the aptness of GAMs (assembled with the mgcv R language package) in comparing and evaluating dissimilar human thermal indices processed with the RayMan Pro model [54,55]; (ii) the importance of energy balance models in obtaining wholesome understandings of thermo-physiological factors that are essential to human thermal comfort evaluations in urban environments [37]; and (iii) the suitability of the selected indices under the examined meteorological conditions.

2. Data and Methods

2.1. Data

To undertake the sensitivity analysis in this study, the required atmospheric data were retrieved from the meteorological station hosted within the Agricultural University of Athens, Greece (Lat $37^{\circ}59'$, long $23^{\circ}42'$, alt 36 m a.s.l). The station itself is located in a planar and unobstructed region within the university campus in Athens, which witnesses hot/dry summers and mild winters, resultant of its encompassing Köppen Geiger climate classification of '*Csa*' [56].

As demonstrated in Table 1, the parameters employed for the analysis were: (i) Air Temperature (T_a) (°C); (ii) Relative Humidity (RH) (%) at a height of 1.5 m, and 3.0 m; (iii) Wind Speed (WS) (m·s⁻¹)

at a height of 3.0 m, and 10 m; (iv) Global Radiation (GR) ($W \cdot m^{-2}$); and, (v) Sunshine Duration (SD) (in minutes per 10 min).

Table 1. Technical characteristics from meteorological station's sensors within Agricultural University of Athens.

Parameter	Sensor Type	Range	Accuracy	Update Interval
Air Temperature (T _a) 1.5 m, 3 m agl *	HD9008TR Delta-OHM	−40−+80 °C	±0.1 °C	5 s without filter
Relative Humidity (RH) 1.5 m, 3 m agl	HD9008TR Delta-OHM	5–98%	±2% for 5–98%	6 s without filter
Wind Speed (WS) 3 m, 10 m agl	AN1 Delta-T Devices	0.2 to 75 ${\rm m}{\cdot}{\rm s}^{-1}$	$\pm 0.1 \text{ m} \cdot \text{s}^{-1}$ for 0.3–10 m $\cdot \text{s}^{-1}$	10 s
Global Radiation (GR)	SKYE SKS 1110	$0-5000 \text{ W} \cdot \text{s}^{-2}$	typ.<3%, max 5%	10 s
Sunshine Duration (SD)	BF3 Delta-T Devices	-	±10% w.r.t. WMO ** definition	10 s

* Above ground level, ** World Meteorological Organization.

The stipulated time interval for the above measurements was 10 min, and the descriptive statistics of the measurements, which were carried out by the equipment described in Table 1 extended between the years of 2002 and 2016. Initially, the raw data consisted of more than 700.000 lines of measurements that were subsequently processed through statistical treatments and corrections, resulting in 338.000 lines of simultaneous and successive data rows. From a climatic perspective, the consequential descriptive statistics of the input parameters were concurrent with those expected from a typical Mediterranean climate (Table 2).

Table 2. Input parameters descriptive statistics.

	Air Temperature 1.5 m (°C)	Vapour Pressure (hPa)	Global Radiation (W/m ²)	Wind Speed (m/s)
Min	-5.1	1.3	0.0	0.2
1st Qu	13.3	9.6	0.0	0.7
Median	19.3	12.9	72.0	1.3
Mean	19.6	13.1	240.0	1.5
3rd Qu	26.0	16.4	451.0	2.1
Max	44.3	31.7	1250.0	7.5

In addition to the climatic parameters, for the configuration of the human energy balance indices, a hypothetical 35 years old male with a height of 1.75 m and weight of 75 kg was assumed, along with a clothing insulation value of 0.9 clo, standing with an activity rate equivalent to 80 W. Although such parameters also play a crucial role in human thermal comfort, given the scope of this particular study, these parameters remained constant in order to strictly focus on the impact of T_a, WS, GR, and VP on the thermal comfort indices sensitivity.

2.2. Thermal Indices

The following indices were respectively employed: THI, HUMIDEX, PET, mPET, UTCI, and PT. As shown in Table 3, these six indices were divided into two 'primary' groups based upon their different integrated calculation model typologies capable of processing the input of singular climatic parameters.

Out of the one hundred and sixty-two thermal indices examined by de Freitas and Grigorieva [16], the six applied in this study fall into the respective categories of 'C' and 'G', representing an Algebraic/Statistical Model and an Energy Balance Model, respectively. It is worth noting that although the new mPET index was not included in the comprehensive list of thermal indices; based upon its close intrinsic revision of the original MEMI model [57], it was upheld within the Energy Balance Model index typology (Figure 1). As indicated by Staiger et al. [20], such a revision can be attributed

to the improvement of the heat transfer simulation resultant of a more efficient bio-heat equation, as presented by Pennes [1].

Table 3. Identification of utilized indices and their respective 'Primary' used in the study against their index model typology. * Added to 'G' category based upon its close association to the MEMI model.

Climatic	Index	Designated	Index Typology
Index	Acronym	Index Label	
Thermohygrometric Index	(THI)	(C)	Algebraic/
HUMIDEX	(HUM)		Statistical Model
Physiologically Equivalent Temperature modified Physiologically Equivalent Temperature Universal Thermal Climate Index Perceived Temperature	(PET) (mPET) * (UTCI) (PT)	(G)	Energy Balance Model

For output applicability purposes and centred upon assessing commonly utilized indices by the international scientific community, the selection of the six indices examined in this study was associated with 'usage popularity'. The justification for the greater use of these indices within built environment investigations can be attributable to: (i) the feasibility to be calibrated from easily obtainable meteorological variables; and, (ii) the base output unit being (°C), hence simplifying the comprehension of such information by non-meteorological experts when approaching human thermal comfort examinations.

Comparatively speaking, and as also suggested by Epstein and Moran [15], the first two indices within the 'C' category are based upon a more simplistic calculation model. Regardless, their application within thermal comfort studies have been present for over half a century, as exemplified by the early disseminations of: (i) Thom [80]/Thom [81], and Angouridakis and Makrogiannis [82] in relation to THI; and, (ii) Masterson and Richardson [4], and Poulton [83] concerning HUMIDEX.

Alternatively, the 'G' category accommodates indices which are constructed upon more intricate and multifarious human thermal regulation models as discussed in numerous studies, including other review articles [14,17,18,20,34,81], and research articles [21,25,84,85]. In addition to these disclosed studies, there has also been a promising amount of interdisciplinary investigations which have utilized the indices to bridge urban biometeorology with other disciplines that can directly scrutinize and improve the thermal responsiveness of the urban public realm.

Particularly embedded at local scales, creative bottom-up approaches associated to architectural and urban planning disciplines are continually integrating several climatic indices described in Figure 1 due to their common output unit, and easily accessible input data [12,13,36,38,41,43,52,86–89].

Overall, and although these interdisciplinary studies have not utilized the same climatic indices, nor in the same methodical manner, there are clear patterns within the international state-of-the-art which suggest their significance as thermal comfort indices, including those from the 'C' category [14]. Even so, comparatively from the six indices, according to Freitas and Grigorieva [17] the four in the 'G' category attained the highest 'total index performance' (based upon the index's 'comprehension', 'scope', 'sophistication', 'transparency', and 'usability' ranking); moreover while the study identified that "there [was] no 'best' index (...), it [was] clear the best performing indices [were] those of the body-atmosphere energy balance variety" (p.21). Correspondingly, and in addition to the SET* index, Staiger et al. [20] similarly recognized the higher application of UTCI, PT, PET, and mPET for human biometeorological evaluations of the urban climate for a multitude of professionals.

Algebraic / Statistical Model Indices 'C'

THI & HUM (

These two climatic indices define human thermal comfort based upon a combination two variables, Ta and RH. On the one hand, this facilitates their application in climatic studies since the two required input variables are measured by all meteorological stations and have been used by the scientific community to determine thermal discomfort in a wide range of climates and environments [e.g., *1, *2, *3, *4, *5, *6]. On the other hand, since they neglect human thermo-regulation factors, they have proven to fall short when individually providing wholesome evaluations of human thermal comfort thresholds [*7, *4, *8, *6].

Energy Balance Model Indices 'G'

PET •



mPET •

In the case of mPET, this index stemmed from the modification and update of the MEMI based model which develops the thermo-regulation model (from a single double-node body model to a multiple-segment model). It also accounts for a new multiple-layer clothing model, which relays to a better scrutiny of the human bio-heat transfer mechanism, that in turn, leads to better estimations of thermo-physiological stress, particularly in periods of more accentuated stimuli [*18, *19, *20, *21].

UTCI •

Introduced by the COST Action 730, this climatic index was also configured to examine the impacts of the outdoor thermal environment upon the human body [*²²]. Centred on the Fiala model, which is an advanced multi-node thermo-physiological system with the ability to predict thermal effects both upon the entire body and extremity regions. In summary, the model consists of two cooperating systems: (i) the controlling active system; and, (ii) the controlled passive system [*²³, *²⁴]. Resultantly, it is has proven appropriate for biometeorological assessments in all climatic zones, as demonstrated by [*²⁵ and, *²⁶].

PT (

This climatic index is well suited for operational applications with high spatial and temporal resolution (e.g. meteorological forecasts). Also, this index has proven its suitability for numerous applications across a wide variety of scales, from micro to global, and is efficaciously used both in daily forecasts and climatological studies. Also designed for outdoor contexts [*²⁷], and similarly, to PET and mPET, PT is the air temperature (°C) of a reference environment in which the perception of heat and/or cold is the same as under the actual conditions.

Figure 1. Descriptive summary of employed climatic indices utilized for human thermal comfort assessments. Figure references: 1 [58], 2 [59], 3 [60], 4 [61], 5 [62], 6 [63], 7 [41], 8 [64], 9 [65], 10 [9], 11 [11], 12 [66], 13 [67], 14 [25], 15 [68], 16 [69], 17 [70], 18 [71], 19 [57], 20 [72], 21 [73], 22 [74], 23 [75], 24 [76], 25 [77], 26 [78], 27 [79].

2.3. Methodology

The purpose of this study is to investigate the sensitivity of each selected index while accounting for its major inputs' variation under different T_a and GR conditions' classes. More specifically, the sensitivity analysis examines the relative consequence of different meteorological input factors (or parameters) on the model output; furthermore, it permits the inspection into how uncertainty in the output of a model (numerical or otherwise) can be apportioned to various sources of uncertainty inherent to the model inputs [90]. One of the most simplistic and straightforward way to conduct sensitivity analysis is to maintain a selected input parameter steady and calculate the climatic index for a spectrum of values for the rest remaining parameters (moving one factor). The results of this method are usually presented as exemplified in Figure 2.



Figure 2. Typical diagrams depicting upon the sensitivity of Predicted Mean Vote and Relative Humidity fluctuation under selected Wind Speed and different clothing insulation values (Modified from Fanger [91]) and American society of heating refrigerating and air-conditioning engineers [92].

The methodological approaches of the sensitivity analysis (and their respective presentation) vary, whereby the identified sensitivities of the disclosed models are distinctive in two principal ways, these being: (1) the variability, or uncertainty, associated with a sensitive input parameter propagating through the model, which results in a large contribution to overall output variability; and, (2) the actual model results being highly correlated with an input parameter, which implies that small changes in input values can imply significant changes in the subsequent outputs. As a result, the methods of sensitivity analysis vary from differential analysis (direct method), one-at-a-time sensitivity measures, factorial design, local/global analysis, to the well-known sensitivity indices or the subjective sensitivity analysis [93–96].

The major drawback of the 'moving one factor' direct methods is that the examined combinations of input parameters' values are very few, and in most cases, are fictional. On the other hand, if one has to examine the impact of the measured inputs' values variation to the model's output values, the cases are finite [27]. As suggested by Ferretti et al. [97], moving one factor at a time away from a fixed baseline in a multidimensional space of uncertain factors renders most of that resulting space unexplored.

Such an occurrence is arguably one of the consequences of the alleged 'curse' of dimensionality, whereby the mass of a hyper-cube tends to concentrate on its edges and corners when increasing dimensionality; corners which are not visited if one moves factors away from their baseline one at a time. Furthermore, moving one factor at a time leaves all interactions dormant, because, in order to activate them, one needs to move more than one factor at a time, a known requirement in the statistical theory of experiment design. These design efforts are, in fact, aimed at uncovering the effects of various orders, e.g., main effects, second-order interactions. Nevertheless, many investigations have reported that numerical experiments do not include design at all. For this specific study, it was chosen to use large data sets with high amounts of real measurements to avoid the aforementioned uncertainties [27,98].

Although this approach is relatively straight forward in terms of biometeorological research, Fanger [91] indicated that "Meteorologists normally give individual parameters independently of each other: air temperature, wind velocity, number of hours sunshine etc. However, for outdoor work and from a recreational point of view, it is the combined effect of the variables which is of interest" (p.58). As a result, this research was conducted through the implementation of a methodology able to reveal the impact of an input parameter on the climatic index's sensitivity under real atmospheric conditions, as established by Charalampopoulos [27]. Similar to this recent study, GAMs were also correspondingly utilised as a means to analyse the sensitivity patterns of the same predetermined climatic indices on their major input's variation. Within Figure 3, an encompassing overview of the undertaken adapted sensitivity analysis of the analysed inputs and related atmospheric parameters classes are summarised, along with the GAM implementation technique for this respective study.

Figure 4 presents an overview representation of the methodical approach and calculation procedures utilised throughout the study, including the use of the R Script to process 'C' labelled climatic indices, and subsequently, the RayMan model for processing the 'G' indices.

The first methodical step undertaken was the respective treatment of the raw data to exclude the outliers, unusually extreme values, and the erroneous data resulting from malfunctions and missing data rows presented by the station's equipment. Alike the initial methodology applied by Charalampopoulos [27], the applied statistical filters take into account the equipment's specifications and restrictions to obtain accurate and sequential data measurements.

The WS data were carried out at 3 m, and 10 m above ground level and for the calculation of UTCI, the 10 m WS measurements were used. To calculate PET, mPET and PT, the WS data measurements at the height of 3 m was then translated into a pedestrian height of 1.5 m through the application of Equation (1) [41,72,98].

$$WS_{hz} = WS_{ho} (h_z/h_o)^a,$$
⁽¹⁾

where WS_{hz} is the WS at the preferred level, WS_{ho} is the WS at the measurements level and a = 0.18 (bushland, orchards). After the data treatment, the dataset was formatted by an R script to become suitable as input text files for the RayMan model. As illustrated in Figures 3 and 4, PET, mPET, UTCI, and PT indices were calculated with the RayMan and an R Script calculated the THI and HUMIDEX. After that, all the results were homogenized and intergraded in matrices for the sensitivity analysis.

After the implementation of the filters and the calculations of the climatic indices were obtained, the semi-parametric extensions of generalized linear models (i.e., GAMs) enabled for smooth functions to fit non-linear response curves to the data. The general structure of the GAMs containing smooth functions is defined as follows:

$$g(\mu) = \beta_0 + s_1(x_1) + s_2(x_2) + \dots + s_i(x_i),$$
(2)

where $g(\mu)$ is the link function connecting the estimated mean to the distribution of the response variable, β_0 is the model intercept, and s_i is the smoothing function to be estimated, and x_i is a predictor [99,100]. Since the GAMs are very sensitive to the sample's size [101], the weather classes' limits are affected by this particularity. Table 4 presents the limits of the GR and T_a classes accompanied by a brief description. Such a distinction of the classified meteorological conditions in classes (in terms of T_a and GR) provides a more detailed sensitivity analysis of the climatic indices. Correspondingly, this enables a better comprehension of climatic index behaviour/sensitivity when exposed to specific meteorological conditions to be found in the built environment. More specifically, Class: (1) represents the predominantly nocturnal periods of the day; (2) represents early morning and late evening periods, and moreover, days with particularly dark skies; (3) represents clear sky conditions with sparse clouds, or fully clear diurnal skies during the winter without any clouds; (4) represents a typical summer diurnal period with clear skies with high exposure to radiation fluxes.

With regards to WS variation, this parameter ranges from 0 to 6.6 m/s and represents 'calm conditions' to a 'moderate breeze'. Notwithstanding, the maximum WS is low, compared to the free atmosphere common conditions, the selected range includes the critical values for the human thermal perception and comfort.



Figure 3. Visual presentation of the sensitivity analysis of the selected climatic indices through the application of Generalized Additive Models (GAMs) to determine specific: (**Up**) Parameter Variation; and, (**Down**) Parameter Change Rate.



Figure 4. The flowchart of the thermal comfort and sensitivity analysis methodology.

Table 4. Stipulated valuable thresholds for the classes of Global Radiation (GR) and Air Tempera	ture
(T _a).	

Class	GR Limits (W/m ²)	Description	T _a Limits (°C)	Description
1	$0 < GR \le 100$	Dark/Night period	$-5 < T_a \le 10$	Cold
2	$100 < \mathrm{GR} \leq 500$	Early Morn./Late Aftern./Days with heavy cloud cover	$10 < T_a \le 20$	Moderate/ Comfortable
3	$500 < GR \le 800$ $100 < CR \le ~1300$	Light cloud cover	$20 < T_a \le 30$ $30 < T_a \le 45$	Warm Hot

3. Results

The sensitivity of the climatic indices under the stipulated meteorological scenarios is shown in the following Figures (for input parameter's variation, and input parameter's change rate) accompanied by tables that contain the summary statistics calculated with normally distributed input parameters to facilitate the numerical interpretation of the obtained results. The figures are graphed with the ggplot2 R-language package [102], and the grey band around the coloured lines (pertaining to each climatic index) is the confidence interval, stipulated at the level of 95%. The results of the analysis reveal the behaviour of the selected thermal comfort indices in terms of sensitivity, under different GR and T_a conditions. The undertaken approach subsequently enables the ensuing corroboration of the variation and change rate of the individual input parameters (i.e., WS, T_a, and Vapour Pressure (VP)).

3.1. Indices Sensitivity to Parameters' Variation

At first sight, the sensitivity of UTCI is clearly higher than the rest of the indices under low global radiation conditions (Class 1), and higher WS increases the sensitivity of the index (Figure 5). All other indices have lower sensitivity in comparison, as seen in Table 5. The higher mean sensitivity under dark conditions (Class 1) after UTCI is presented by the mPET index and is equal to 0.41 °C/10 min. It is also worth noting that UTCI increases in sensitivity rather rapidly when WS increases; on the other hand, all the other indices remain almost constant and horizontal during this augmentation of WS.

The examination of the sensitivity to WS when the radiation classes increases, demonstrates increased sensitivity of the other 'G' label climatic indices, and as expected, a constant and horizontal

sensitivity for the climatic indices with a 'C' label. In Class 3, the UTCI sensitivity trend is close to the rest 'G' indices. In Class 4, the higher sensitivity is demonstrated by the PET and mPET indices in light of WS variation.



Figure 5. The sensitivity of the indices to Wind Speed (WS) variation under different Global Radiation (GR) conditions.

Table 5. Descriptive statistics of the indices' sensitivity to Wind Speed (WS) under different Global Radiation (GR) conditions. THI (Thermohygrometric Index), HUM (HUMIDEX), UTCI (Universal Thermal Climate Index), PET (Physiologically Equivalent Temperature), mPET (modified PET), PT (Perceived Temperature).

		THI	HUM	UTCI	PET	mPET	РТ
	Mean	0.11	0.14	1.56	0.30	0.41	0.24
Class 1	Max	0.16	0.23	2.89	0.44	0.56	0.47
Class 1	Min	0.09	0.12	0.74	0.25	0.35	0.20
	Median	0.10	0.13	1.44	0.29	0.40	0.22
	Mean	0.14	0.21	1.70	0.96	0.97	0.70
Class 2	Max	0.35	0.51	3.20	1.90	1.53	1.55
Class 2	Min	0.11	0.16	1.10	0.75	0.82	0.53
	Median	0.13	0.19	1.50	0.86	0.94	0.65
	Mean	0.12	0.22	1.19	1.05	0.92	0.66
Class 2	Max	0.21	0.37	2.17	2.09	1.57	1.41
Class 5	Min	0.10	0.18	0.88	0.83	0.75	0.50
	Median	0.11	0.20	0.99	0.95	0.88	0.60
	Mean	0.12	0.23	0.80	1.04	0.84	0.58
Class 4	Max	0.22	0.44	1.24	2.72	1.97	1.46
CIdSS 4	Min	0.09	0.18	0.50	0.57	0.65	0.37
	Median	0.11	0.22	0.78	0.86	0.74	0.49

Overall, it can be identified that mPET, PET and PT rise in sensitivity from Class 1 to Class 2 and after that, they keep their sensitivity to WS almost constant. On the other hand, UTCI's sensitivity declines from Class 2 to Class 4. Additionally, the sensitivity is modified positively by the increment of WS, especially for UTCI (unlike mPET, PET and PT that revealed less variation in such circumstances).

The sensitivity of the selected indices to T_a under different GR conditions reveals a general pattern with a high sensitivity of the UTCI to low T_a , which decreases as T_a rises (Figure 6). On the other hand,

the rest 'G' climatic indices have relatively low sensitivity under low GR conditions (e.g., Class 1), and their sensitivity increases with the gradual increment of GR. Contrariwise, and as expected, the type 'C' climatic indices have low and constant sensitivity to T_a .



Figure 6. The sensitivity of the indices to Air Temperature (T_a) variation under different GR conditions.

It is noteworthy that when T_a exceeds 20 °C (i.e., Class 2 to 4), the sensitivity of PET and mPET surpasses the sensitivity of UTCI. Such a result illustrates that when the weather is particularly hot and sunny, the PET and mPET indices are more sensitive than UTCI. The descriptive statistics (Table 6) provide a quantitative outlook of the indices' sensitivity estimation between the four respective classes. In addition, it is possible to verify that the 'C' indices are stable no matter the GR Class or T_a variation. Considering the descriptive statistics of the indices' sensitivity, one can note that the mean sensitivity of UTCI to T_a variation remains almost constant. In contrast, in these same conditions, PET's mean sensitivity increases almost three times from Class 1 to Class 4. The rest of the 'G' indices increase their sensitivity to T_a almost twofold for the same changes of GR.

		THI	HUM	UTCI	PET	mPET	РТ
	Mean	0.12	0.18	1.13	0.48	0.48	0.40
Class 1	Max	0.17	0.31	2.45	1.59	1.35	0.66
	Min	0.08	0.08	0.53	0.23	0.34	0.20
	Median	0.12	0.16	0.95	0.35	0.38	0.41
	Mean	0.18	0.26	1.38	1.05	0.92	0.78
Class 2	Max	0.29	0.32	2.43	1.33	1.11	1.06
Class 2	Min	0.11	0.06	0.51	0.67	0.50	0.42
	Median	0.16	0.26	1.22	1.07	0.97	0.82
	Mean	0.15	0.23	1.40	1.14	0.95	0.76
Class 2	Max	0.27	0.26	3.60	1.42	1.26	1.26
Class 5	Min	0.09	0.18	0.50	0.77	0.51	0.30
	Median	0.14	0.23	1.10	1.23	1.07	0.87
	Mean	0.13	0.24	1.21	1.20	0.98	0.72
Class 4	Max	0.19	0.27	2.72	1.50	1.40	1.08
C1455 4	Min	0.08	0.21	0.36	0.50	0.29	0.20
	Median	0.13	0.24	1.01	1.40	1.09	0.93

Table 6. Descriptive statistics of the indices' sensitivity to T_a under different GR conditions.

Figure 7 illustrates the indices' sensitivity to VP under different GR classes. Under lower radiation conditions, when the VP is low, the UTCI's sensitivity is very high in comparison to all the other indices (both from 'C' and 'G' typologies). The sensitivity of this index lowers as the VP rises and reaches the rest of the indices for VP higher than 25 hPa. Resultantly, during night-time or very dark conditions, the relative sensitivity of UTCI is very high when the atmosphere is dry. The increment of GR (Class 2 and 3) leads to a higher sensitivity of PET, mPET and PT, yet and as expected, the sensitivity of both THI and HUMIDEX remains constant. Under very sunny conditions (Class 4) the sensitivity's behaviour is different due to UTCI being more sensitive under dry conditions. This being said, the sensitivity of the UTCI decreases right after 7 hPa, and the PET's sensitivity surpasses that of the UTCI, and after 10 hPa, mPET also exceeds the UTCI's sensitivity.



Figure 7. The sensitivity of the indices to Vapour Pressure (VP) variation under different GR conditions.

According to the statistics in Table 7, the mean UTCI sensitivity to VP variation is almost stable between the GR classes, but PET, mPET and PT sensitivity increases from the Class 1 to Class 4. It must, however, be noted that UTCI has restrictions for VP exceeding that of 20 hPa [78,103,104]. As a result, this constraint should be considered when perceiving the outcomes for this specific climatic index.

		THI	HUM	UTCI	PET	mPET	PT
	Mean	0.11	0.17	0.91	0.35	0.36	0.35
Class 1	Max	0.17	0.20	1.93	0.41	0.42	0.48
Class 1	Min	0.08	0.14	0.32	0.15	0.18	0.24
	Median	0.11	0.17	0.73	0.36	0.37	0.35
	Mean	0.16	0.27	1.23	1.10	0.98	0.86
Class 2	Max	0.17	0.30	2.46	1.30	1.07	0.99
Class 2	Min	0.14	0.19	0.69	0.80	0.85	0.71
	Median	0.17	0.29	1.04	1.20	1.00	0.88
	Mean	0.13	0.24	1.09	1.15	0.93	0.77
Class 2	Max	0.16	0.28	2.64	1.28	1.10	1.17
Class 5	Min	0.12	0.18	0.55	0.77	0.75	0.40
	Median	0.13	0.24	0.78	1.16	0.90	0.75
	Mean	0.12	0.24	0.92	1.13	0.87	0.65
Class 4	Max	0.12	0.27	1.94	1.38	1.19	0.87
CIdSS 4	Min	0.11	0.22	0.56	0.82	0.58	0.47
	Median	0.12	0.24	0.69	1.07	0.80	0.57

Table 7. Descriptive statistics of the indices' sensitivity to Vapour Pressure (VP) under different GR conditions.

Shown in Figure 8 and Table 8, it is obvious that UTCI has the highest sensitivity when the temperature is low (Class 1). The mean sensitivity to WS variation is four times higher than the succeeding index, mPET. The formed pattern indicates a distinct quantitative behaviour of UTCI in comparison to all the other indices from both the 'G' and 'C' typologies. Although to a lower extent, the same pattern is present in the case of Class 2. Generally, the WS variation does not significantly affect the response of the indices, except UTCI, regardless of the T_a class.



Figure 8. The sensitivity of the indices to Wind Speed (WS) variation under different T_a conditions.

Comparing the summary statistics in Table 8, it is possible to identify a slight increment of the sensitivity to WS given the augmentation of T_a . For Class 4, which is the warmest among the other classes, the higher mean sensitivity was presented by the PET index, followed by mPET. In addition, it is worth mentioning that the mean sensitivity of UTCI decreased significantly from Class 1 to Class 4. On the other hand, the sensitivity of PET increased during the same class range. Thus and when considering the sensitivity patterns and statistics, it is clear that Ta and WS are comparatively weak stimuli.

		THI	HUM	UTCI	PET	mPET	РТ
	Mean	0.12	0.12	2.00	0.37	0.50	0.30
C 1 1	Max	0.23	0.28	3.60	0.63	0.80	0.59
Class 1	Min	0.10	0.09	1.10	0.17	0.40	0.23
	Median	0.11	0.11	1.90	0.38	0.50	0.29
	Mean	0.12	0.17	1.62	0.63	0.69	0.42
C1 0	Max	0.19	0.26	2.80	0.72	0.92	0.66
Class 2	Min	0.11	0.15	0.87	0.57	0.59	0.36
	Median	0.11	0.16	1.49	0.62	0.66	0.40
	Mean	0.13	0.24	1.05	0.98	0.91	0.74
C 1	Max	0.19	0.36	2.04	1.28	1.40	1.10
Class 3	Min	0.10	0.19	0.70	0.79	0.66	0.56
	Median	0.12	0.22	0.93	0.93	0.84	0.68
	Mean	0.11	0.24	0.52	0.96	0.72	0.48
Class 4	Max	0.18	0.40	0.80	1.55	1.14	0.85
Class 4	Min	0.09	0.20	0.33	0.81	0.63	0.40
	Median	0.10	0.21	0.50	0.90	0.69	0.45

Table 8. Descriptive statistics of the indices' sensitivity to WS under different T_a conditions.

3.2. Indices Sensitivity to Parameters' Change Rate

In order to study the indices' behaviour to input parameters' changes, the GAM analysis was utilised to ascertain the major input parameters' change rates. The results shed light on the ability of the indices to 'react' rapidly, smoothly or slowly to the changes of the input parameters. This type of approach is common in the sensitivity analysis of indices or equations [27,85,93,105]. The sensitivity to the WS change rate under different GR classes (Figure 9) reveals a distinguished behaviour of UTCI in comparison to the other 'G' indices. Under dark conditions (Class 1) the gradient of the UTCI's sensitivity is very steep. In contrast, 'C' indices have a linear, yet horizontal sensitivity pattern, as anticipated due to their inherent algebraic equation.



Figure 9. The sensitivity of the indices to WS change rate under different GR conditions.

Furthermore, as the GR increased, so did the sensitivity of PET, mPET and PT. It is worth noting that under sunny conditions (Class 4), the higher sensitivity to WS changes was presented by PET, closely followed by mPET. In the case of UTCI, its sensitivity lowered as GR increased. Such behaviour contradicted the sensitivity from the other 'G' indices, which increased in sensitivity, albeit with a gentler gradient. More specifically, in Table 9 it was possible to verify that under dark conditions (Class 1), the mean sensitivity of UTCI was four times higher than the mean under sunny conditions (Class 4). Adjacently, it was also possible to observe a very high maximum sensitivity of the UTCI to the WS change rate in both Class 2 and 3. These values were 11.56 and 13.09 °C/10 min, respectively, and have been calculated for WS change rates higher than 2.0 m·s⁻¹/10 min. In the case of UTCI, given a rapid increment of WS in Class 2 and 3, its increase was drastic, changing more than 10 °C in 10 min.

In Figure 10 and Table 10, it is possible to verify the results of the sensitivity analysis in light of T_a change rates under different GR conditions. When approaching the rates themselves, the T_a change rates were very narrow for Class 4 and wide in the case of Class 2. This divergence is to be expected when accounting for high GR values frequently being measured for a limited number of hours during the diurnal period. Overall, however, PET revealed to be the most sensitive to T_a change rates, particularly for Classes 2 to 4. The patterns of index sensitivity in these classes are also almost linear and diverge from similar points of low T_a change rates.

		THI	HUM	UTCI	PET	mPET	PT
	Mean	0.30	0.40	4.82	0.98	1.35	0.79
Class 1	Max	0.63	0.85	10.14	2.40	3.31	1.74
Class 1	Min	0.11	0.15	0.56	0.28	0.25	0.24
	Median	0.19	0.23	4.56	0.64	1.05	0.50
	Mean	0.16	0.23	5.00	2.40	2.40	1.69
C1	Max	0.19	0.30	11.56	6.00	5.51	4.56
Class 2	Min	0.14	0.21	0.96	1.10	0.91	0.77
	Median	0.16	0.22	4.34	1.90	1.99	1.25
	Mean	0.17	0.28	3.20	2.41	2.09	1.45
Class 2	Max	0.32	0.38	13.09	4.45	4.74	2.85
Class 5	Min	0.13	0.24	0.71	0.85	0.68	0.56
	Median	0.14	0.27	2.19	2.36	1.95	1.39
	Mean	0.13	0.26	1.22	2.05	1.56	1.01
Class 4	Max	0.14	0.29	1.52	2.88	2.28	1.39
Class 4	Min	0.12	0.24	0.62	0.67	0.52	0.43
	Median	0.13	0.26	1.36	2.27	1.70	1.08

Table 9. Descriptive statistics of the indices' sensitivity to WS change rates under different GR conditions.



Figure 10. The sensitivity of the indices to the T_a change rate under different GR conditions.

The statistic measurements reveal high sensitivity values under medium GR conditions (Class 2 and 3), and low sensitivity to T_a change rates under sunny conditions (Class 4). Additionally, and within Class 3, the highest maximum sensitivity of 14.33 °C/10 min was obtained for PET. In terms of mean sensitivity, Class 2 presented the highest value of 7.38 °C/10 min, obtained by the PET index.

The patterns which are illustrated in the graphs and the statistics measurements reveal a grouping of PET, mPET, PT indices, and a distinctive behaviour of UTCI. Also, it is possible to verify the anticipated linear behaviour of 'C' indices, with notable similarities for Classes 1 to 3. The sensitivity to VP change rates' (as illustrated in Figure 11) has two dominant characteristics, the: (i) higher uncertainty of the estimations; and, (ii) low gradient presented by the index lines. Visibly, it is likewise possible to verify the low impact of VP on the sensitivity of the analysed climatic indices.

		THI	HUM	UTCI	PET	mPET	РТ
	Mean	1.55	2.32	2.69	2.87	1.96	2.09
	Max	3.06	5.23	5.34	5.71	4.66	4.59
Class 1	Min	0.04	0.06	0.88	0.24	0.29	0.22
	Median	1.55	2.18	2.41	2.83	1.67	1.88
	Mean	1.86	2.86	4.90	7.38	4.97	4.30
	Max	5.35	7.89	12.60	14.14	13.44	12.74
Class 2	Min	0.05	0.09	1.10	0.91	0.82	0.65
	Median	1.18	2.00	4.00	7.61	3.76	2.32
	Mean	1.02	1.76	3.23	6.75	4.17	3.40
C 1	Max	2.56	4.28	7.18	14.33	11.37	9.44
Class 3	Min	0.04	0.10	0.85	0.98	0.78	0.62
	Median	0.81	1.39	2.75	6.37	2.82	2.27
	Mean	0.34	0.69	1.38	1.81	1.34	0.99
Class 4	Max	0.58	1.29	2.13	3.38	2.66	2.24
Class 4	Min	0.05	0.11	0.62	0.89	0.67	0.18
	Median	0.33	0.71	1.43	1.63	1.14	0.74

Table 10. Descriptive statistics of the indices' sensitivity to T_a change rates under different GR conditions.



Figure 11. The sensitivity of the indices to the VP change rate under different GR conditions.

In conjunction, and still focusing on the results presented by Figure 11, for the first time in the study, the sensitivity of the 'G' indices is as low as those presented by the 'C' typology. Amongst the other indices, both PET and mPET are the most sensitive. PT has the highest mean and maximum sensitivity under Class 3 and 4, increasing its values in accordance with the VP change rate. Despite the modification of the thermoregulation model of the mPET, the mPET is not more sensitive than PET to VP change rates. According to the graphs and the statistics (Figure 11/Table 11), UTCI presented a moderate sensitivity in comparison to the other examined indices indicating that its' model reacts similarly to the rest of them.

		THI	HUM	UTCI	PET	mPET	РТ
	Mean	0.70	1.50	1.22	0.79	0.78	1.48
Class 1	Max	0.99	2.10	1.59	0.99	1.10	2.42
Class 1	Min	0.08	0.10	0.42	0.29	0.23	0.25
	Median	0.78	1.70	1.24	0.81	0.81	1.55
	Mean	0.58	1.20	1.60	2.10	1.75	1.84
Class 2	Max	1.28	2.70	3.40	4.80	3.95	3.62
Class 2	Min	0.14	0.20	1.10	1.00	0.88	0.72
	Median	0.55	1.20	1.40	1.90	1.52	1.74
	Mean	0.51	1.06	1.04	1.35	1.10	1.55
Class 2	Max	1.23	2.55	1.13	1.77	1.10	2.92
Class 5	Min	0.11	0.20	0.93	0.96	0.90	0.72
	Median	0.40	0.84	1.06	1.31	1.10	1.40
	Mean	0.49	1.01	0.90	1.19	0.94	1.49
Class 4	Max	1.31	2.74	1.01	1.41	1.06	3.18
C1455 4	Min	0.10	0.19	0.74	0.77	0.79	0.54
	Median	0.38	0.81	0.92	1.18	0.96	1.29

Table 11. Descriptive statistics of the indices' sensitivity to VP change rates under different GR conditions.

Lastly, the final part of the calculation examined the sensitivity of the selected indices to WS change rates under different T_a conditions (Figure 12). The behaviour presented by the UTCI is significant in this circumstance, due to its steep gradient and high values for the first three Classes. It is clear that UTCI is overreacting to the WS changes, so one must count a change of 12 °C/10 min when the WS is changing with a rate of ~4 m·s⁻¹/10 min.



Figure 12. The sensitivity of the indices to WS variation under different T_a conditions.

Moreover, one can identify that the UTCI's sensitivity is almost three times higher than the rest of the 'G' indices, as shown in Table 12. This being said, as T_a raises, the sensitivity differences decrease, and in Class 4, PET is the most sensitive amongst all the examined indices investigated in this study.

		THI	HUM	UTCI	PET	mPET	РТ
Class 1	Mean	0.19	0.20	4.78	0.91	1.30	0.75
	Max	0.34	0.50	8.67	1.90	2.77	1.85
	Min	0.13	0.13	0.81	0.32	0.29	0.26
	Median	0.16	0.15	4.88	0.79	1.16	0.62
Class 2	Mean	0.26	0.34	5.62	1.80	1.98	1.24
	Max	0.44	0.59	12.45	5.20	5.19	3.63
	Min	0.12	0.17	0.73	0.50	0.43	0.36
	Median	0.21	0.27	4.98	1.40	1.63	0.89
Class 3	Mean	0.26	0.46	2.62	1.59	1.59	1.22
	Max	0.49	0.93	5.89	1.90	2.22	1.60
	Min	0.12	0.22	0.62	0.69	0.57	0.54
	Median	0.15	0.29	2.29	1.82	1.74	1.33
Class 4	Mean	0.12	0.26	0.87	1.60	1.17	0.71
	Max	0.15	0.33	1.00	2.19	1.62	0.85
	Min	0.06	0.14	0.54	0.75	0.58	0.45
	Median	0.12	0.26	0.93	1.70	1.23	0.77

Table 12. Descriptive statistics of the indices' sensitivity to WS change rates under different T_a conditions.

4. Discussion

The analysis of the results shed light on the behaviour of the selected indices under the different stipulated atmospheric conditions. Firstly, it was noted that the indices could be grouped into three distinct categories from a statistical sensitivity point of view. The 'C' category (the algebraic indices) presented a very low sensitivity, in comparison to the rest of the indices, no matter the GR and T_a class, nor the variation and change rate of the WS, VP and T_a parameters. This behaviour was partly expected when taking into account the input parameters, the equations of the related indices, and the outcomes of previously published studies in this field [27,41,59,106,107]. The next group contains the PET, mPET and PT indices, which presented similar qualitative and quantitative behaviour under all classes and conditions. Also, their sensitivity indicated the ability to follow the fluctuations of the input parameters which relate effectively to existing human thermal comfort thresholds. These findings are in agreement with the recent papers of Nouri et al. [72], and Coccolo et al. [18]. The last group contains the UTCI index, which is capable of rapidly expressing the impact of atmospheric environmental changes on human thermal perception, especially in dark and windy conditions. Such a behaviour has also been identified by other studies, including in [77,104,108,109].

Analysing the statistics and figures of the examined scenarios, it was found that UTCI is the most sensitive to WS variations index among the selected indices under low GR conditions (GR Class 1 & 2). As the GR increases (such as in GR Class 3) the sensitivity of the UTCI to WS lowers when the sensitivity of the remaining 'G' category increases. These two divergences rendered an identifiable group of similar patterns. In the case of the highest GR conditions (GR Class 4), the mPET and PET generally surpassed the UTCI's sensitivity to WS variation. Analogous patterns and descriptive statistics were also found during the examination of the indices' sensitivity analysis to the WS change range under diverging GR conditions. Since the sensitivity of the indices to WS variation and change rate under different GR classes were examined, it was required to interpret the findings of previous studies that focused on both atmospheric parameters. As a result, the pinpointed distinct behaviour of UTCI to WS variation is corroborated by adjacent studies, including [27,77,106]. In addition, the GR results confirm the findings of Provençal et al. [106] regarding the higher sensitivity of PET, and the findings of Charalampopoulos [27] for the UTCI's sensitivity patterns to variation and change rates of radiation fluxes in urban environments. For this reason, the analysis of the results strengthen the identified high sensitivity of the UTCI to WS variation (and change rate) under low GR conditions and the superior sensitivity of PET and mPET under sunny conditions.

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Moving to the results of the sensitivity analysis to T_a under different GR classes, it was found that UTCI losses sensitivity as the T_a and GR increase. On the other hand, the other 'G' category indices gain sensitivity when they go from lower to higher GR classes. It is noteworthy to mention that UTCI is almost five times more sensitive than the other 'G' indices when GR and T_a are low (GR Class 1, and close to 0 °C, respectively). This behaviour could set the UTCI as the most appropriate to express the human thermal environment under cold and dark conditions, but at the same time, it is very difficult to conclude if this very high sensitivity is in accordance to the real thermo-physiological behaviour of the human body. The results are in accordance with the combined findings of [27] for the variation (and the change rate) of T_a and GR. Under this logic, if one must evaluate the human thermal environment under cold be more appropriate for the same type of thermal comfort evaluation. In terms of T_a change rate, PET, mPET and PT can react more rapidly to the T_a changes, so they seem to be more appropriate for transitional thermal environments such as semi-outdoor or partially shaded open spaces under hot conditions.

The next inputs parameters' combination for the sensitivity analysis examined the influence of VP variation (and change rate) under different GR classes. The gradient of the sensitivity patterns accompanied by the summary statistics proves that VP has a weak influence on 'G' category indices' fluctuation. This finding is in agreement with the results of [27], but when examining the comparative indices' sensitivity, those results are partially in contrary with the results of [106] since they found that the UTCI is less sensitive than PET and mPET. According to analysis undertaken by this study, the UTCI is more sensitive than PET and mPET under lower VP environments, but less so for conditions with high VP values. It was noted however, that this divergence lowers as GR increases. At this point, it must be noted that UTCI is restricted by default under 20 hPa [77], so the results taken for this index are debatable.

The examination of indices' sensitivity to WS variation and change rate, under different T_a classes, indicates a low and relatively stable behaviour. The graphs and the descriptive statistics reveal an almost stable indices' sensitivity to WS variation. Only the UTCI index fluctuates considerably under T_a Class1 and Class2 conditions, having the highest sensitivity among the selected indices. The above findings are in agreement with the results of Charalampopoulos [27] and Provençal et al. [106] which confirm the low sensitivity to WS and the comparatively higher sensitivity of UTCI. Additionally, it was found that as T_a increases, the UTCI sensitivity lowered, and under hot conditions (Class 4, 30 °C < $T_a \leq$ ~45 °C) the UTCI presented lower mean sensitivity in comparison to the cases of PET's and mPET's. This is an indication that PET and mPET are more capable of expressing the thermal environment under hot and sunny conditions, inclusively when taking into account the WS variation, and change rate.

Examining the behaviour of the 'C' category indices (THI and HUMIDEX) from the sensitivity point of view, behaved as expected given their input parameters and equations. On the other hand, these indices were a measurement of the GAMs methodology correctness. Since their equations are simpler and more linear, it was easier to predict their behaviour. As a result, their linear, stable and low sensitivity aids to confirm that the study's methodology is able to reveal the different behaviour of the selected indices. In turn, this enables the fortification that 'C' category indices are less apt at wholesomely evaluating human thermal comfort thresholds in light of different environmental stimuli. Such a fortification is in conformity with the findings of adjacent research outputs presented by [27,59,106,107].

5. Conclusions

This article aimed to examine the sensitivity of the most widely used thermal comfort indices against their major input variables under different classified conditions of global radiation and air temperature. The sensitivity has been analysed according to two approaches. The first one focuses on the sensitivity of each index to the input parameter's variance, and the second focuses on the sensitivity of the index to the change rate of the input parameter. The results were carried out by utilizing a long period input dataset that includes every season of the year through the use of generalised additive models with R-language scripting and the RayMan model. Overall, it can be concluded that Generalised Additive Models can provide an adequate solution for the investigation of sensitivity analysis of big, yet chaotic datasets, and are able to provide reasonable results for this type of analysis.

When approaching the indices' behaviour, UTCI is the most sensitive under cold and dark (i.e., with low GR) conditions, and PET is the most sensitive under hot and sunny conditions. Such a result is indicative of the indices' suitability for specific atmospheric conditions and meteorological contexts. Generally, UTCI is oversensitive under dark conditions (as demonstrated in Class 1), especially to WS variation, and WS change rate variation. Moreover, the PET index is the most sensitive to high T_a and high GR conditions, suggesting its relevance for the wholesome investigation of human thermal comfort under hot/sunny conditions. Such pertinence is even more salient when assessing thermal stress during summer periods in sunny places. The mPET is less sensitive than PET, especially during periods of higher stimuli, but as it remains derivative from the MEMI model, it still presents similar behaviour patterns and sensitivity to PET. Nevertheless, its attenuated variation during periods of higher stimuli potentially reveals its enhanced applicability in such climatic scenarios. Also, PT sensitivity's behaviour is distinctive but does not deviate far from PET and mPET. Generally, however, this is the least sensitive index of the 'G' group.

Speaking about the input parameters, GR is a very influential parameter for the sensitivity of the energy balance model indices, thus also suggesting the limitation for algebraic/statistical models to undertake complete evaluations of outdoor human thermal comfort thresholds. Thus far, this result is concomitant with the majority of studies of human thermal comfort evaluations, which in turn enforce the imperativeness of also evaluating the influence of non-temperature variables.

To conclude, adjacent to the growing body of knowledge aimed at developing better evaluations of the human condition in urban environments, this study emphasised not only the importance of climatic indices but moreover, their comparative efficiency in assessing human thermal comfort thresholds in different atmospheric conditions and environments. As with all maturing topics, it is clear that further work is required to deepen our understanding of thermal comfort conditions; nevertheless, and as suggested by state-of-the-art and individual results specific to this study, enough is already known to broaden the horizon of climatic indices, and transpose this knowledge into other disciplines. In future research it is intended to conduct thorough statistical analysis obtained through the continued use of GAMs' in thermal comfort index studies. Additionally, an analysis focused on the diurnal and nocturnal time periods could shed more light on the behaviour of the indices under typical conditions. In this way, efforts at addressing existing and future thermo-physiological risk factors in outdoor urban environments can be grasped by non-climatic experts to ensure safe, comfortable, and active environments through climate-sensitive design and decision making in a century prone to further climatic aggravations.

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