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Communication

Sensitivity Analysis of Heat Stress Indices

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Abstract: More than 40 heat indices are being used across the world to quantify outdoor thermal comfort. The selection of an Outdoor Heat Stress Index (OHSI) depends on several parameters, including clothing, age, awareness, local environment, food consumption, human activities, and resources. This study investigates various indicators of heat stress, including (i) OHSIs officially used to quantify heat stress worldwide, (ii) the estimation methods of these indices, and (iii) the sensitivity analysis of indices, namely, Corrected Effective Temperature (CET), Heat Index (HI), Wet Bulb Globe Temperature (WBGT), Universal Thermal Climate Index (UTCI), Discomfort Index (DI), Summer Simmer Index (SSI), and Predicted Mean Vote (PMV). The results indicate the degree of sensitivity of indices, with the HI being the most sensitive for estimating heat stress. Additionally, the WBGT, HI, and CET are recommended indices that can be directly measured using sensors instead of relying on calculated indices that are based on estimation techniques and some ideal physical assumptions.

Keywords: heat stress indices; sensitivity; variation coefficient; thermal comfort; public health

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1. Introduction

Heat stress is a condition that can result from prolonged exposure to high temperatures and humidity. It can range in severity from mild discomfort to a life-threatening medical emergency, depending on the individual's susceptibility and the intensity and duration of the heat exposure [1]. It usually occurs when the body is unable to maintain a healthy temperature in response to a hot environment [2]. Heat stress can negatively affect public health and quality of life in both urban and rural areas [3,4]. It can lead to heavy sweating, muscle cramps, headaches, and decreased productivity [5,6]. Moreover, exposure to extreme heat can harm the body and lungs, exacerbating respiratory conditions such as asthma, particularly when breathing hot and humid air [7].

In different countries, heat stress is quantified with the help of specific indices. The thermal stress index is a quantitative measure that integrates one or more of the physical, thermal, and personal factors effecting heat transfer between the environment and a person [8]. Many heat stress indices have been developed and classified based on thermal comfort assessment, physiological strain, physical factors of the environment, and "rational" heat balance equation [9]. The thermal comfort of an individual depends mainly on the individual's activities and other factors including behavioral activities, age group, health condition, and local climate and environment [10]. The collective factors are presented in Table 1. Elderly individuals and young children are particularly sensitive to heat stress due to their weaker tolerance for extreme heat events and greater need for comfort [11].

In relation to heat stress, rational heat measures refer to methods for assessing the thermal environment and predicting its effects on human health and comfort [12]. The factors listed in Table 1 can be used to evaluate the vulnerability of residents to heat stress. To address heat stress issues, different countries have adopted various techniques for assessing thermal comfort, such as Wet Bulb Global Temperature (WBGT), Heat Stress Index (HSI), and Thermal Work Limit (TWL). These indices are commonly used by climate, environmental, and national weather agencies [13]. Most indices can be directly measured and calibrated using equations, while others require the use of different models and methods.

Table 1. Important factors involved in heat stress.

Environmental	Physiological	Behavioral
Air temperature	Age	Activity
Wind velocity	Gender	Clothing
Relative humidity	Health status (body temperature, rate of heartbeat, blood pressure)	Insulation
Mean radiant temperature	Sweat rate	Posture
Globe temperature		
Location		

Urban areas are often subject to higher temperatures due to factors such as the absorption and re-emission of heat by buildings and pavement, reduced vegetation cover, air pollution, and increased energy use. However, it should be noted that rising temperatures can also affect rural areas, particularly in the context of climate change, with some rural areas warming up faster than nearby urban areas [14,15].

This study is justified by the lack of arguments on the use of so many indices existing throughout the world to quantify the heat stress indices in different regions. Our hypothesis is that some parameters have a significant impact on different heat stress indices, while others may have a negligible effect.

Our research questions were as follows: What is the inventory of different External Heat Stress Indices (OHSI) around the world?; What are their current estimation methods?; How do CET, HI, SSI, PMV, DI, WBGT, and UTCI react to changes in different parameters?; What parameter variations induce changes from comfortable zone to warmer zones in the available thermal comfort scales? Our goal was to analyze the most commonly used ones by understanding their variation trend and exhibiting the most sensitive heat index parameters.

Therefore, the objectives of this study are to conduct a survey for OHSI officially used around the world, to analyze estimation methods of heat stress and currently available modified thermal comfort scales, and to perform a sensitivity analysis of CET, HI, SSI, PMV, DI, WBGT, and UTCI.

The novelty of this study lies in its comprehensive analysis of various heat stress indices used around the world, providing a unique perspective on their sensitivity to different relevant parameters. This sensitivity analysis is carried out for indices with available formula in two ways: 1. By using the partial derivatives with respect to their explanatory variables; and 2. By exploring the effect on the comfort zones of the realistic variations of the variables involved in the heat stress index considered. The first is theoretically valid for infinitesimal variations, while the second is obtained by simulating the value of the thermal stress index for chosen feasible values of its variables.

The structure of this paper is as follows: Section 2 presents the research methodology, Section 3 provides direct formulas for estimating different heat stress indices, Section 4 presents a survey map of the OHSI used across the world by official agencies, Sections 5 and 6 discusses the results of sensitivity and thermal comfort scale variations, and Section 7 provides the conclusions and future perspectives.

2. Materials and Methods

The adopted methodology in our current study is described in Figure 1. The data were collected through OHSI surveys on internet sources, listed in Appendix A Table A1. Following this, sensitivity analysis of OHSI was performed based on updated estimation models.

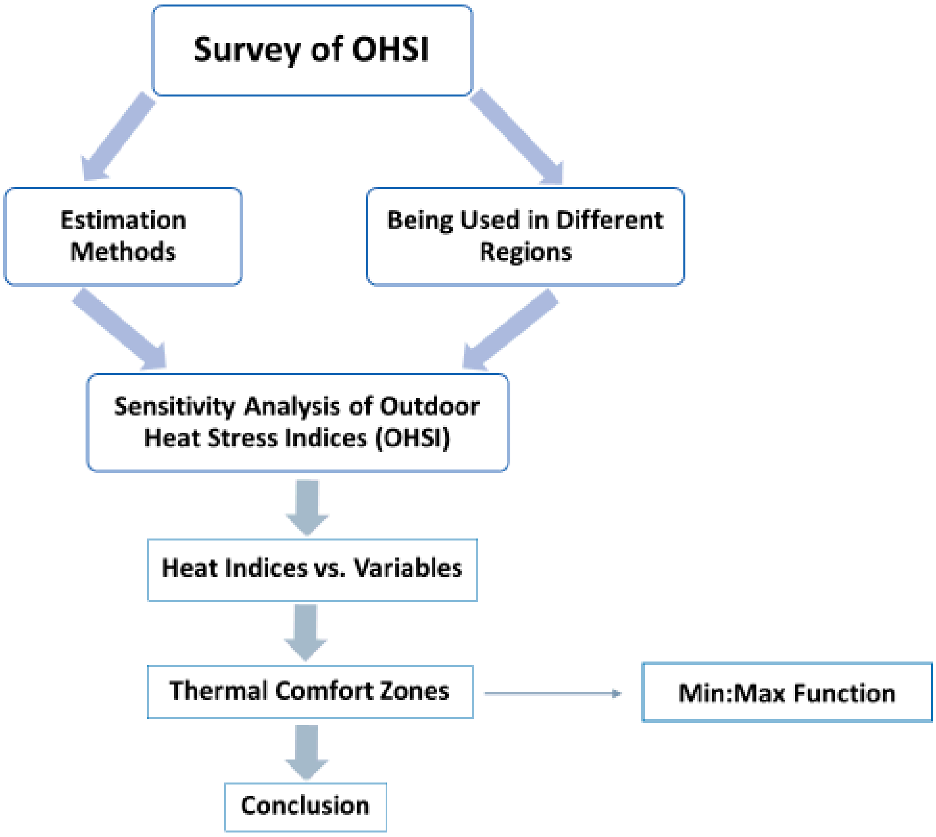

Figure 1. Schematic diagram of the adopted methodology: This figure presents a visual representation of the workflow used in this study for the sensitivity analysis of heat stress indices. It outlines the steps taken from data collection to analysis, providing a clear overview of the research process.

The sensitivity of heat stress indices is paramount in understanding their real-world implications. A highly sensitive index might offer precise readings in specific conditions but may falter in others. On the other hand, a less sensitive index might provide a broader overview but miss nuances. This study delves into the sensitivity of various indices, highlighting their strengths and weaknesses, and offering recommendations for their optimal use.

The mathematical models of heat stress indices were computed to quantify the sensitivity of indices and evolving variables, such as air temperature and humidity. In addition, the process of identifying the range of values for each variable that corresponds to thermal comfort was conducted using minimum and maximum functions.

3. Estimation of Outdoor Thermal Indices

Heat stress can be quantified using more than 40 indices worldwide [16]. These indices are classified into three groups: "direct," "empirical," and "rational." While direct indices are simpler and can be monitored using instruments like Kestrel [17], KIMO [18], and WBGT meter [19] in both indoor and outdoor environments, rational and empirical indices are more complex. These indices take into account meteorological, physiological, and behavioral factors, making it difficult to estimate thermal stress for an individual. To differentiate between empirical and rational indices, empirical indices rely on statistical analysis of observed data, while rational indices use physical models to estimate heat stress. Table 2 provides calibration methods and formulas for the 16 most commonly used OHSIs depicted from the relevant references in this paper. Other possible OHSIs may be studied by the reader by following our proposed methodology.

Table 2. Outdoor heat stress indices and their methods for estimation.

Heat Stress Indices	Formula	Nomenclature
WBGT: Wet bulb globe temperature [20]	$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$	C_{res} = heat exchange by convection in breathing E_c = heat exchange by evaporation on the skin E_{res} = evaporative heat exchange in breathing Eq = required evaporative heat $Emax$ = maximum evaporative heat H = sensitive heat losses met = metabolic rate T_{mrt} = mean radiant temperature mw = effective mechanical power RH = relative humidity SR = solar radiation T_w = wet-bulb temperature T_a = air temperature T_g = globe temperature v = wind speed/ air velocity vp = vapor pressure
UTCI: Universal Thermal Climate Index [21–23]	Calculated by 6th-order polynomial $UTCI = f(T_a; T_{mrt}; RH; v)$ $UTCI = 3.21 + 0.872T_a + 0.2459T_{mrt} - 2.5078v - 0.0176RH$	
HSI: Heat stress index [24]	$HSI = \frac{100Eq}{Emax}$	
Out_SET: Outdoor standard effective temperature [25]	$OUT\_SET = (WBGT - 11.76)/0.405$	
ESI: Environmental Stress Index [26]	$ESI = 0.62T_a - 0.007RH + 0.002.SR + 0.0043 \cdot (T_a \cdot RH) - 0.078 \cdot (0.1 + SR)^{-1}$	
PMV: Predicted Mean Vote [27,28]	$PMV = \left(0.303e^{-2.1\times met} + 0.028\right) \times (met - mw)\underbrace{-H - E_c - C_{res} - E_{res}}_{\alpha}$	
CET: Corrected Effective Temperature [29]	$CET = \left(1.21T_g - 0.21T_w\right)/\left(1 + 0.029\left(T_g - T_w\right)\right)$	
DI: Discomfort Index [30]	$DI = T_a - 0.55(1 - 0.01RH)(T_a - 14.5)$	
TSI: Tropical summer index [31]	$TSI = 1/3T_w + 3/4T_g - 2v^{1/2}$	
ECI: Equatorial comfort Index [32]	$ECI = 0.574T_a + 0.271vp - 1.81v^{1/2} + 4.2$	
HU: Humidex [33]	$HU = T_a + (5/9)(e - 10)$ $e = 6.11 \times e^{5417.7530\times\left(\frac{1}{273.16} - \frac{1}{\text{Dewpoint in Kelvin}}\right)}$	
SSI: Summer simmer index [34]	$SSI = 1.98(T_a - (0.55 - 0.0055.RH)(T_a - 58)) - 56.83$	
OI: Oxford index [35]	$OI = 0.85T_w + 0.15T_a$	
ASV: Actual Sensation Vote value for Europe [36]	$ASV = 0.049T_a + 0.001.SR - 0.051v + 0.014.RH - 2.079$	
AT: Australian apparent temperature [37]	$AT = T_a + 0.33vp - 0.70v - 4.00$	
HI: Heat index [38]	$HI = -42.379 + 2.05.T_a + 10.14.RH - 0.22.T_a.RH - 6.84 \times 10^{-3}.T_a^2 - 5.48 \times 10^{-2}.RH^2 + 1.23 \times 10^{-3}.T_a^2.RH + 8.5 \times 10^{-4}.T_a.RH^2 - 1.99 \times 10^{-6}.T_a^2.RH^2$	

Important Remark: Each heat index has different assumptions/calibrations (such as body size, physical fitness, etc.) that consider temperature and humidity differently. A high-heat-stress event indicated by one index does not necessarily transfer to another index. For example, the original equation for WBGT was derived and calibrated using US Marine Corps Marines during basic training [39] and in good physical condition. HI was calibrated for an "average" American male [40]. We bring the attention of the reader only to the indices which can be measured using sensors, i.e., CET, HSI, HI, WBGT, and Thermal Work Limit (TWL). All other indices presented in Table 2 are also estimated using their respective formulas or physical models that depend on assumptions e.g., age group, activities, clothing, area, etc., but cannot be directly measured.

4. Outdoor Heat Indices in Different Regions

Different regions in the world, characterized by unique climatic conditions such as sub-tropical, tropical, and Mediterranean climates, influence human thermal conditions and physiology in distinct ways. Many countries monitor heat stress using a variety of parameters and indicators to inform locals about heat event warnings. Parameters like air temperature, relative humidity, global radiation, and wind speed are commonly used in the measurement of heat stress indices.

The WBGT is the most widely used index in various countries including Australia, the U.S.A, Europe, Japan, and Colombia. This is primarily because it can be measured by sensors and estimated by a simple mathematical equation. The choice of the heat index depends on several factors specific to an area such as weather patterns (hot and dry, semi-humid, cold winter regions, etc.), the age group of the population (elderly, children, youth), and activities.

To provide a comprehensive view of the indices used worldwide, we conducted a survey study. The results of this survey, including the agencies officially involved in the assessment of heat stress, are presented in Appendix A and visually represented in Figure 2.

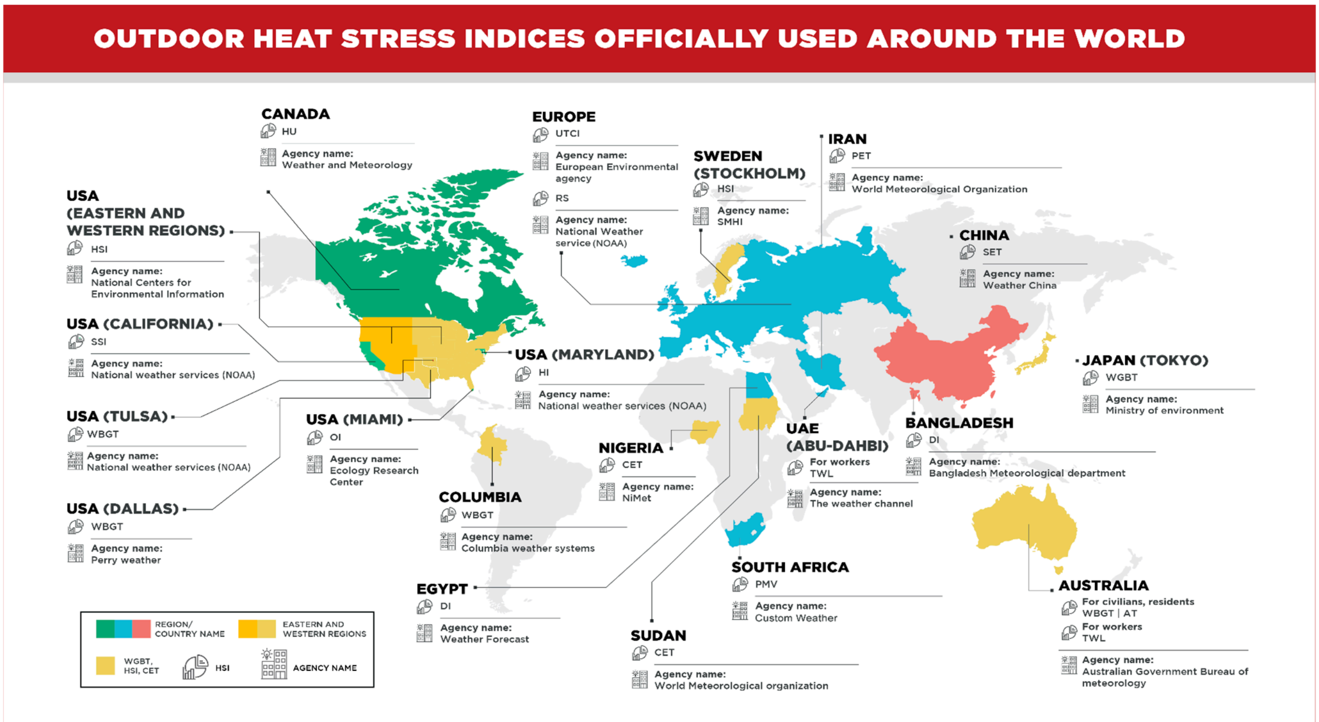

Figure 2. Global distribution of Outdoor Heat Stress Indices: This map illustrates the different indices officially used around the world. Each country is color-coded based on the specific index it uses, providing a global perspective on the prevalence and distribution of these indices.

5. Sensitivity Analysis

5.1. Sensitivity Analysis of Heat Indices versus Variables

In this section, we aim to investigate the sensitivity of heat stress indices to small variations around a reference point. To achieve this, we employ a multi-variable partial differential equation to analyze the sensitivities of the following operational indices: HI, WBGT, PMV, SSI, CET, DI, and UTCI. Simulations are started by defining a set of values (S_0) for the input parameters that correspond to the comfort zone.

Table 3 gives the values for S_0, where the input values for each index have been selected based on a comfortable situation. For example, with T_{go} = 45 °C and T_{wo} = 16.27 °C, CET indicates comfortable conditions, but small variations could lead to slight discomfort.

Subsequently, the sensitivity of each index is computed with respect to small variations around the reference values.

Consider a heat index y as a function of explicative variables $x_1, \ldots, x_n$, that is,

$$y = f(x_1, \ldots, x_n) \tag{1}$$

where y (thermal index) is the function of x (input variables e.g., T_g, T_a, T_{mrt}, RH, v, T_w, met, mw). Then, a small variation of y can be expressed as

$$\Delta y = \left.\frac{\partial f}{\partial x_1}\right|_0 \Delta x_1 + \left.\frac{\partial f}{\partial x_2}\right|_0 \Delta x_2 + \ldots + \left.\frac{\partial f}{\partial x_n}\right|_0 \Delta x_n \tag{2}$$

Table 3. Sensitivity analysis of heat stress indices.

Heat Stress Indices	S_0	Sensitivity around S_0	Partial Differential
CET	CET_o = 27.83 °C T_{go} = 45 °C $T_{\omega o}$ = 16.27 °C	$\left.\frac{\partial CET}{\partial T_g}\right\|_0 = 0.19$ $\left.\frac{\partial CET}{\partial T_w}\right\|_0 = -0.08$	$\left.\frac{\partial CET}{\partial T_g}\right\|_0 = \frac{1.21[1+0.029(T_{g0}-T_{\omega_0})]-1.21\times 0.029\times T_{g0}}{[1+0.029(T_{g0}-T_{\omega_0})]^2}$ $\left.\frac{\partial CET}{\partial T_w}\right\|_0 = \frac{-0.21[1+0.029(T_{g0}-T_{\omega_0})]+0.21\times T_{\omega_0}\times 0.029}{[1+0.029(T_{g0}-T_{\omega_0})]^2}$
PMV	PMV_o = 0.379 met_0 = 1.68 mw_0 = 0.1 α = −0.33	$\left.\frac{\partial PMV}{\partial met}\right\|_0 = 3.6\times10^{-3}$ $\left.\frac{\partial PMV}{\partial mw}\right\|_0 = -3.6\times10^{-2}$ $\left.\frac{\partial PMV}{\partial \alpha}\right\|_0 = -0.33$	$\left.\frac{\partial PMV}{\partial m}\right\|_0 = \beta$ *where* $\beta = -2.1\times 0.303\times e^{-2.1m_0}\times m_0 + 0.303\times e^{-2.1m_0} + 0.028 - 2.1\times 0.303\times e^{-2.1m_0}\times \omega_0$ $\left.\frac{\partial PMV}{\partial \omega}\right\|_0 = -0.028 - 0.303\times e^{-2.1m_0}$ $\left.\frac{\partial PMV}{\partial \alpha}\right\|_0 = -1$
HI	HI_o = 78.74 °F T_{ao} = 81 °F RH_0 = 30%	$\left.\frac{\partial HI}{\partial T_{ao}}\right\|_0 = 1.71$ $\left.\frac{\partial HI}{\partial RH}\right\|_0 = 0.32$	$\left.\frac{\partial HI}{\partial T}\right\|_0 = 2.049 - 0.22RH_0 - 2\left(6.84\times10^{-3}\right)(T_{ao}) + 2\left(1.22\times10^{-3}\right)(T_{ao})(RH_0) + 8.5\times10^{-4}(RH_0)^2 - 1.99\times10^{-6}(T_{ao})(RH_0)^2$ $\left.\frac{\partial HI}{\partial RH}\right\|_0 = 10.143 - 0.22(T_{ao}) - 2\left(5.48\times10^{-2}\right)(RH_0) + 1.22\times10^{-3}(T_{ao})^2 + 2\left(8.5\times10^{-4}\right)(T_{ao})(RH_0) - 2\left(1.99\times10^{-6}\right)(T_{ao})^2(RH_0)$
SSI	SSI_o = 78.52 °F T_{ao} = 81 °F RH_0 = 30%	$\left.\frac{\partial SSI}{\partial T_{ao}}\right\|_0 = 0.89$ $\left.\frac{\partial SSI}{\partial RH}\right\|_0 = 0.25$	$\left.\frac{\partial SSI}{\partial T}\right\|_0 = 1.98(0.45 + 0.0055RH_0)$ $\left.\frac{\partial SSI}{\partial RH}\right\|_0 = 1.98[0.0055T_{ao} - 0.0055(58)]$
DI	DI_o = 20.24 °C T_{ao} = 27.22 °C RH_0 = 30%	$\left.\frac{\partial DI}{\partial T_{ao}}\right\|_0 = 0.452$ $\left.\frac{\partial DI}{\partial RH}\right\|_0 = 0.07$	$\left.\frac{\partial DI}{\partial T}\right\|_0 = 0.45 + 0.0055RH_0$ $\left.\frac{\partial DI}{\partial RH}\right\|_0 = 0.0055T_{ao} - 0.07975$
WBGT	$WBGT_o$ = 23.11 °C T_{go} = 45 °C $T_{\omega o}$ = 16.27 °C T_{ao} = 27.22 °C	$\left.\frac{\partial WBGT}{\partial T_g}\right\|_0 = 0.2$ $\left.\frac{\partial WBGT}{\partial T_w}\right\|_0 = 0.7$ $\left.\frac{\partial WBGT}{\partial T_{ao}}\right\|_0 = 0.1$	$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$
UTCI	$UTCI_0$ = 28.52 °C T_{ao} = 27.22 °C T_{mrt} = 27 °C v_o = 2 m/s RH_0 = 30%	$\left.\frac{\partial UTCI}{\partial T_{ao}}\right\|_0 = 0.87$ $\left.\frac{\partial UTCI}{\partial RH}\right\|_0 = -1.76\times10^{-2}$ $\left.\frac{\partial UTCI}{\partial T_{mrt}}\right\|_0 = 0.24$ $\left.\frac{\partial UTCI}{\partial v}\right\|_0 = -2.5$	$UTCI = 3.21 + 0.872T_a + 0.2459T_{mrt} - 2.5078v - 0.0176RH$

This study is relevant to know the trend of the variation and to exhibit the most sensitive parameters in the heat index:

- A positive sign means that the index increased with the parameter, whereas a negative sign means that the index increases (resp. decreases) when the parameter decreases (resp. increases);
- A high value of sensitivity means a high influence of the corresponding parameter on the given index;
- We can see that relative humidity has a negligible impact on DI and UTCI.

5.2. Variations in Thermal Comfort Zones versus Heat Indices

In this section, we analyze the influence of variables for widely used heat indices. More precisely, simulations have been performed for the parameter ranges for each thermal comfort zone defined according to the referenced Table 4.

Table 4. Reference comfort scale for widely used Thermal Stress Indices.

Comfort Zone (Z)	WBGT °C	CET °C	UTCI °C	PMV	DI °C	SSI °F	HI °F
extreme cold stress (Z-5).			<−40	−3–−2.5			
very strong cold stress (Z-4)			−35–−25				
strong cold stress (Z-3)			−25–−13	−2.5–−1.5			
moderate cold (Z-2)	<17	<17	−13–0	−1.5–−0.5			
slightly cold (Z-1)			0–8	−0.5–0			
comfortable (Z0)		17–30	8–25	0–0.5		77–83	
slightly warm (Z1)	17–23	30–34	25–31	0.5–1.5	22–24	83–91	
moderate warm (Z2)	23–28	34–45	31–37	1.5–2.5	24–28	91–100	80–91
strong heat stress (Z3)	28–30	45–49	37–46	2.5–3	>28	100–112	90–105
very hot (Z4)	>30		46 to above	3		112–125	105–130
extremely dangerous (Z5)		>49		>3		125–150	>130

The formulas presented in Table 2 from references [20–38] were used to analyze the sensitivity of discomfort zones. The input mentioned in Table 3 was used to simulate each index, and it was observed that the HI, WBGT, and UTCI results indicated a different comfort zone, as shown in Table 5 with color codes. It was also noticed that, due to the significant variation coefficient of HI, a small increase in its variables could lead to an increase in the level of discomfort, while the results for other indices remained in the same comfort zone. Further, x1, … xn were simulated by using the min–max function, where xmin is the lowest possible (S0) and xmax is maximum possible value under realistic situations in the summer season ($T_g = 50, T_a = 50\ ^\circ\mathrm{C}, T_{mrt} = 50\ ^\circ\mathrm{C}, RH = 100\%$, $v = 10\mathrm{m/s}$, $T_w = 25\ ^\circ\mathrm{C}$, $met = 4, mw = 0.9, \alpha = -3$). The simulations were performed by changing only one variable at each time step. The obtained results are plotted and shown in Figure 3, which demonstrates the sensitivity of heat indices showing different thermal discomfort zones within the same range. The use of sensors and instruments for measuring the variables can significantly reduce errors and improve the accuracy of these simulations. This approach provides a more comprehensive understanding of how different variables can influence thermal discomfort, which is crucial for designing appropriate intervention strategies to mitigate the negative impacts of heat stress on human health and productivity. Therefore, it is recommended to use sensors and measure the variables accurately and continuously to obtain reliable data. Simultaneously, this can avoid over- and underestimation of heat stress.

Table 5. Sensitivity of comfort level—this table illustrates the variations in comfort levels across different heat indices, highlighting the differential responses to environmental parameters.

Index	y	Δy
HI	78.74	80.78
SSI	78.52	79.67
PMV	0.37	0.29
WBGT	23.11	23.11
UTCI	28.52	28.52
CET	27.83	27.94
DI	20.24	20.76

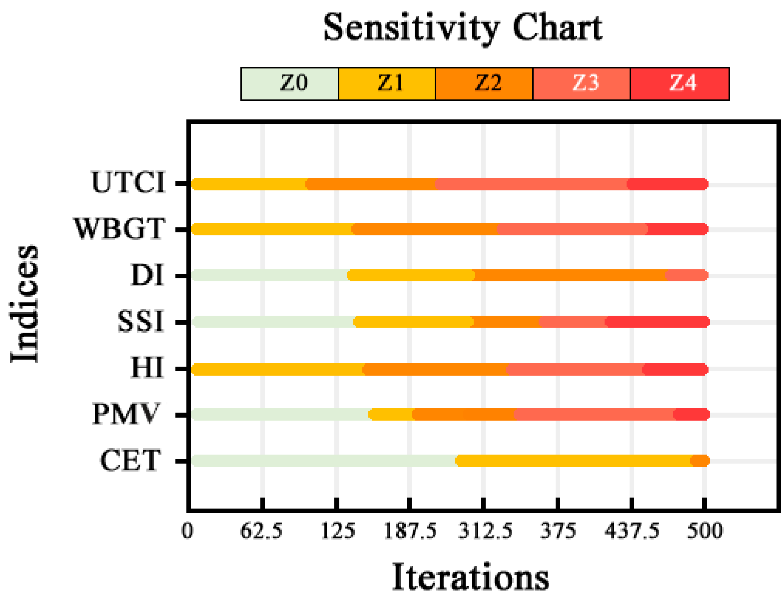

Figure 3. Sensitivity analysis of Simulated Heat Stress Indices: This visualization illustrates the responsiveness of each heat stress index to variations in environmental parameters. By comparing the indices, readers can discern the relative sensitivity of each, understanding which indices might be more robust or susceptible to specific changes in conditions. Such insights are crucial for policymakers and researchers aiming to select or design indices that are both accurate and resilient to varying climatic scenarios.

6. Discussion

The findings of this research, as discussed in Table 6, shed light on the effectiveness of simulated indices, their advantages, associated challenges, and recommendations for their application. The innovation of this paper lies in its comprehensive analysis of heat stress indices, provides understanding that can guide policymakers and researchers.

Table 6. Comparative analysis of simulated indices.

Heat Stress Indices	Effectiveness	Advantage	Limitation	Recommendation
WBGT	Effective with direct solar radiation and high humidity.	It is a comprehensive measure for heat stress that can be calibrated directly by using sensors.	It does not account for wind speed and clothing insulation, which can affect the perceived temperature.	It is recommended for outdoor activities.
CET	Effective in humid regions, making it suitable for tropical climates.	Incorporates modern adjustments to older indices, improving calibration accuracy.	Underestimates outdoor heat stress with varying conditions.	Best suited for indoor environments.
UTCI	Effective in a variety of climates and conditions from cold to hot and dry to humid.	It integrates air temperature, wind speed, humidity, and solar radiation.	Requires a complex calculation.	Suitable for urban planning and public health advisories.
PMV	PMV is effective in controlled indoor environments.	It provides a complete scale to indicate the level of human comfort.	Requires detailed input data for accurate prediction, making calibration complex.	Ideal for building design and HVAC system optimization.
DI	Effective in various climates.	Simple to calculate and can be measured directly by using sensors.	Primarily considers temperature and humidity, which might not be sufficient in extreme conditions. Limited scale for indicating thermal discomfort.	Suitable for general weather forecasts and public advisories.

Table 6. *Cont.*

Heat Stress Indices	Effectiveness	Advantage	Limitation	Recommendation
SSI	Effective in hot and high-humidity conditions.	Defined thermal comfort scale for hot conditions.	Limited to summer season.	Useful for public health advisories during summer months.
HI	Adaptable to a range of hot conditions, especially in high humidity.	Simple calculations and can be measured by sensors.	Sensitive and might not be effective in dry or extremely cold conditions.	Useful for high-humidity areas.

7. Conclusions

This study concludes that every region across the globe chooses heat indices according to some specific parameters. The factors that influence the selection are awareness among people (especially vulnerable ones), physical interviews (knowing about the age, sex, sensations, clothing styles, and activities), the correlation between immune systems, and the number of heart-health events. While numerous countries prioritize other environmental concerns overheat stress indices, it is essential to recognize that each country's choice of index is influenced by its unique climatic conditions and challenges. The comprehensive analysis of seven OHSIs (CET, WBGT, UTCI, HI, DI, SSI, PMV) was programmed and simulated to analyze the variation coefficient of their evolving parameters. The study provides a foundation for understanding of indices effectiveness and advantages. While each index has its unique strengths and limitations, their collective evaluation offers a holistic perspective on heat stress assessment. The results show that air temperature is the most sensitive parameter, especially for estimating HI, SSI, DI, and UTCI, whereas relative humidity is negligibly sensitive except in the case of SSI and HI. It is crucial for countries to consider mean radiant temperature in their indices, given its profound impact on perceived temperature and comfort.

In conclusion, we recommend the use of sensor-measurable indices such as WBGT, HI, and CET. Sensors and instruments are a more reliable method for measuring heat stress compared to mathematical models. It can avoid error by directly measuring parameters such as temperature, humidity, and air velocity, while models rely on assumptions that may not accurately reflect the actual conditions. Real-time measurements from sensors and instruments are critical in rapidly changing environments, such as industrial settings or during athletic events, and they provide more detailed information about the distribution of heat stress. While mathematical models have their advantages, they are often based on simplifications and assumptions that may not be as reliable as direct measurements. Overall, sensors and instruments are the preferred choice for accurately measuring heat stress in real-world settings.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. List of Outdoor thermal Stress Indices are officially used in Countries.

Region/ Country Name	TSI	Evolve Parameters	Sources	Agency Name
Columbia	WBGT	T_w, T_a, T_g, RH, v	https://columbiaweather.com/products/weather-stations/wet-bulb-globe-temperature/ (accessed on 4 November 2021).	Columbia weather systems
Dallas	WBGT		https://perryweather.com/weather-station/ (accessed 4 November on 2021).	Perry weather
Tulsa			https://www.weather.gov/arx/wbgt (accessed on 4 November 2021).	National weather services
California	SSI (Pacific Ocean and Mediterranean weather)	RH, T_a in Fahrenheit	https://www.weather.gov/ (accessed on 8 October 2021).	
Maryland	Heat index (elder population)		https://www.weather.gov/safety/heat-index (accessed on 11 November 2021).	NOAA National Weather Services (Weather prediction center)
Miami	Oxford Index	T_w, T_a	https://www.miamioh.edu/cas/academics/centers/erc/weather-station/index.html (accessed on 11 November 2021).	Ecology Research Center
Eastern and western regions	HSI	T_a, RH, M, convective heat exchange, radiant heat exchange, v	https://www.ncdc.noaa.gov/societal-impacts/heat-stress/climatology (accessed on 11 November 2021).	National Centers for Environmental Information
Australia	WBGT (for civilians)	T_w, T_a, T_g, RH, v	http://www.bom.gov.au/ (accessed on 11 November 2021).	Australian Government Bureau of meteorology
	AT (for workers)	T_a, RH, v		
	TWL	Physiological data like height, age, sweat rate, T_a, T_w, T_g.		
Japan (Tokyo)	WBGT	T_w, T_a, T_g, RH, WS	https://mainichi.jp/english/articles/20180719/p2a/00m/0na/004000c (accessed on 18 November 2021).	Ministry of environment
Europe	UTCI (semi humid hot summer and cold winter regions)	T_a, Average radiation temperature, WS, RH	https://climate-adapt.eea.europa.eu/knowledge/european-climate-data-explorer/health/thermal-comfort-indices-universal-thermal-climate-index#details (accessed on 15 December 2022).	European Environmental agency
	Required Sweating	RH, Sweat rate, M	https://www.weather.gov/oun/safety-summer-heathumidity (accessed on 11 November 2021).	National Weather service (W.S)
South Africa	PMV (overrated summertime sensation and underestimated in winter)	I_{cl}, M, RH, T_{mrt}.	https://customweather.com/ (accessed on 11 November 2021).	Pietermaritzburg, South Africa

Table A1. *Cont.*

Region/ Country Name	TSI	Evolve Parameters	Sources	Agency Name
China	SET (subtropical regions)	RH, v, M, radiation temperature, T_w, T_a	http://en.weather.com.cn/ (accessed on 15 December 2022).	Weather China
Sweden (Stockholm)	HSI (elderly population)	T_a, RH, M, convective heat exchange, radiant heat exchange, WS	https://www.smhi.se/en/q/Stockholm/2673730 (accessed on 15 December 2022).	SMHI
UAE (Abu Dhabi)	TWL (occupational) for workers	Physiological data like height, age, sweat rate, T_a, T_w, T_g	https://weather.com/weather/today/l/Abu+Dhabi+Abu+Dhabi+Emirate+United+Arab+Emirates?placeId=0755f9b1a0f85388ca0d9510010eed3e6274c95ec9ecc1a8353af4782d304238 (accessed on 15 December 2022).	The weather channels
Bangladesh	DI	T_a, RH	http://live.bmd.gov.bd/ (accessed on 15 December 2022).	Bangladesh Meteorological department
Egypt	DI (hot dry climate)		https://www.weather-forecast.com/maps/Egypt (accessed on 15 December 2022).	Weather Forecast
Sudan	CET	T_g, T_w, RH, v	https://worldweather.wmo.int/en/country.html?countryCode=203 (accessed on 15 December 2022).	World Meteorological organization (M.D)
Nigeria	CET		https://www.nimet.gov.ng/ (accessed on 15 December 2022).	NiMet (M.D)
Iran	PET (hot dry climate)	T_a, v	https://worldweather.wmo.int/en/country.html?countryCode=114 (accessed on 15 December 2022).	World Meteorological Organization
Canada	HU (humid weather patterns)	T_a, dew point temperature, RH factor, molecular weight of water, latent heat and gas constant	http://ec.gc.ca/meteo-weather/default.asp?lang=En (accessed on 11 June 2023).	Weather and Meteorology. Retrieved 19 May 2016

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