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Perspective

Which Thermal Index for Which Purpose? A Practical Guide to Simple Heat Indices and Equivalent Temperatures for Users

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Abstract: More than one hundred thermal indices are in use, and each new study seems to add another. For people who want to apply an index—in weather services, public health, occupational safety, urban planning, tourism or sports—the question is not which index is scientifically the most elaborate, but which one answers their question. This perspective gives a practical overview of nine indices that dominate application today: the empirical Heat Index (HI) and Discomfort Index (DI), the occupational screening index Wet Bulb Globe Temperature (WBGT), which is well established but not founded on thermophysiology, the thermal comfort index Predicted Mean Vote (PMV), which rests on a simplified heat balance, and the heat-balance equivalent temperatures Physiologically Equivalent Temperature (PET), modified PET (mPET), Universal Thermal Climate Index (UTCI), Perceived Temperature (PT) and Standard Effective Temperature (SET*). For each index, the purpose it was built for, the input variables, the assumptions about the human being, typical fields of application, strengths and limitations are summarised. Three tables condense the comparison, translate it into a simple decision path and compare PET, mPET and UTCI. The main message is simple: an index is a tool made for a purpose. Simple indices remain useful where radiation and wind are of minor importance or where data are scarce; equivalent temperatures based on the human energy balance are needed whenever sun, shade, wind and surfaces matter, that is, in most outdoor situations. Whatever index is chosen, its assumptions, its input data—above all the mean radiant temperature in sunshine—and its assessment scale must be reported transparently.

Keywords: thermal indices; heat stress; PET; UTCI; mean radiant temperature; human biometeorology

1. Introduction

Weather and climate act on the human being through a combination of air temperature, humidity, wind and radiation, together with activity and clothing. Since the early twentieth century, researchers have tried to condense this combination into a single number that ordinary people and decision makers can understand. The result is a large and still growing family of thermal indices. De Freitas and Grigorieva catalogued 165 indices and simulation devices [1], and their later appraisal shows how different the concepts, assumptions and quality of these indices are [2]. Staiger et al. proposed criteria for selecting suitable indices for human-biometeorological studies and recommended only a small number of them [3]. Recent comparisons on campuses and in parks, and recent reviews

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of outdoor thermal comfort studies, confirm that the performance of an index depends on climate, site and local calibration [4–7].

For users outside the core community of human biometeorology, the situation is confusing. A heat warning in the United States is based on the Heat Index, a sports federation refers to the WBGT, a German city climate analysis uses PET, the German Meteorological Service (DWD) issues warnings based on the Perceived Temperature, and many international studies prefer UTCI. All of these numbers are expressed in degrees Celsius, which suggests that they are comparable. They are not. The same weather situation can produce values that differ by more than 10 K, simply because the indices assume different persons, different reference environments and different ways of dealing with radiation and wind.

This perspective does not propose another index. It is written for those who want to apply an existing one. It explains in simple terms what the most frequently used indices were designed for, what they can and cannot do, and how to choose between them. The focus is on application, in the spirit that the purpose determines the method.

2. Purpose and Aim of This Guide

The purpose of this perspective is to provide a short and reliable orientation for users of thermal indices, in particular:

- national meteorological and hydrological services and public health authorities that design heat or cold warning systems and heat–health action plans;
- occupational health and safety professionals and organisers of sports and mass events;
- urban and landscape planners, architects and consultants who assess the thermal effect of buildings, trees, shading and surfaces;
- researchers in epidemiology, tourism and climate impact studies who need an exposure metric.

The aim is threefold: (i) to describe nine widely used indices with their origin, assumptions and inputs; (ii) to compare their advantages and limitations in a way that can be understood without a background in thermophysiology; and (iii) to offer a simple decision path that links a practical question to a suitable index.

3. Three Groups of Indices

Thermal indices can be grouped into three groups according to the principle on which they are built. Empirical indices (HI, DI) combine air temperature and humidity into an index value with an empirical or regression formula. They are easy to compute and to communicate, but they do not represent the heat exchange of the human body. Screening indices (WBGT) were developed for occupational and military heat-stress control: they combine a few measured or estimated variables with fixed weights and are linked to reference values for work and sport. They are well established, but they are not models of the human body and not founded on thermophysiology. Together, empirical and screening indices are called simple indices in this perspective; in the classification of Binarti et al. [7] both belong to the linear-equation approach, from which the rational indices developed. Heat-balance indices calculate the heat fluxes between body and environment—convection, radiation, evaporation, respiration and conduction—for a defined person with defined activity and clothing. They developed from the one-node model of Fanger (PMV) via the two-node models of Gagge (SET*) and the Munich Energy-balance Model for Individuals (PET) to the multi-node models of Fiala (UTCI, mPET) [7]. The PMV is a thermal comfort index and not a thermal stress index, and it rests on a simplified steady-state heat balance and not on the full energy balance with thermoregulation; it expresses the result as a thermal sensation vote [7]; the other indices discussed here are expressed as an equivalent temperature: the air temperature of a defined reference environment in which the person would experience the same thermal state (for example, the same skin and core temperature or the same thermal strain) as in the actual environment. The boundaries between the groups are not sharp, but the grouping shows what each index was built for.

The heat-balance indices share one decisive input: the mean radiant temperature (T_{mrt}), which summarises all short- and long-wave radiant fluxes that reach the human body. Outdoors on a sunny day with little wind, T_{mrt} can exceed air temperature by 30 K or more and then dominates the thermal load; under overcast skies, at night or in strong wind its influence is smaller, and air temperature, wind, humidity and activity gain weight. A recent synthesis of outdoor studies found air temperature to be the strongest single driver of PET and UTCI across climates and seasons, with globe temperature showing the closest relationship to both indices [8]. How T_{mrt} is measured or modelled can therefore be at least as important as the choice of index when the sun is shining [9–11].

4. Simple Indices: Empirical and Screening Indices

4.1. Heat Index (HI)

The Heat Index goes back to Steadman [12], who derived an "apparent temperature" for sultry conditions from a detailed body model of an adult walking outdoors in the shade in light wind. The operational version of the US National Weather Service is a regression fit to Steadman's tables [13] and uses only air temperature and relative humidity. It is well known to the public in North America and widely used in epidemiology because it can be calculated from standard station data [14].

Advantages: simple, widely known, originally based on a physiological model, good communication value. Limitations: radiation and wind are not considered, so the index describes shade conditions only; the regression is valid mainly above about 27 °C and moderate humidity; several calculation algorithms are in use and give different values [14]; for very hot and humid conditions, Steadman's original model runs outside its range, which is why Lu and Romps proposed an extended formulation [15]. The HI is not suited for cold conditions or for planning questions where sun and shade differ.

4.2. Discomfort Index (DI)

Thom [16] introduced the Discomfort Index (originally "Temperature–Humidity Index") to describe summer discomfort in buildings and cities in the United States. In the Celsius form it reads $DI = T_a - 0.55\,(1 - 0.01\,RH)(T_a - 14.5)$, with air temperature T_a in °C and relative humidity RH in %. Discomfort classes were later adapted, for example for heat waves in Greece [17].

Advantages: very simple; long time series can be computed from historical records; useful for climatological comparisons in warm and humid regions. Limitations: like the HI, it ignores radiation, wind, activity and clothing; the class limits are empirical and region-dependent; it does not describe cold stress. The DI is best seen as a historical and climatological indicator, not as a basis for warnings or planning.

4.3. Wet Bulb Globe Temperature (WBGT)

The WBGT was developed by Yaglou and Minard [18] to control heat casualties during military training in the United States. Outdoors it is calculated as $WBGT = 0.7\,T_{nw} + 0.2\,T_g + 0.1\,T_a$, where T_{nw} is the natural wet-bulb temperature and T_g the temperature of a black globe of 150 mm diameter. It is standardised in ISO 7243 [19], which links WBGT reference values to metabolic rate and acclimatisation, and it is the most widely used index in occupational health and sports medicine [20].

Advantages: includes the effect of radiation and wind through the instruments; reference values for work and sport exist; long practical experience. Limitations: it is a screening index, not a thermophysiological model; clothing must be handled by correction values; when the special instruments are not available, WBGT has to be estimated from meteorological data, and the estimation methods differ considerably [21,22]; it gives no information on cold stress; under conditions of limited evaporation it may underestimate strain [23]. If WBGT reference values are exceeded, ISO 7243 itself recommends a more detailed analysis, for example with the Predicted Heat Strain model [24].

From the perspective of radiation, the WBGT needs a critical look. Its radiation term is the temperature of a 150 mm black globe, weighted with only 0.2. The black sphere absorbs about 95% of short-wave radiation instead of about 70% for skin and clothing; it presents the same cross-section to the sun at every sun elevation, whereas a standing person receives most direct radiation from a low sun; and it needs about 10 min or more to follow a change between sun and shade [25]; recent field data from urban sites confirm that a globe-shaped sensor differs from a body-shaped sensor in the longwave and diffuse shortwave radiation it receives [26]. The globe therefore misrepresents the radiant load of a standing person, most strongly at high sun, while the radiation signal that finally reaches the WBGT through the globe term is small and depends strongly on wind. The same change in radiation that shifts the WBGT by a few kelvin changes energy-balance indices such as PET and UTCI considerably more [25,27]. The empirical weights of the WBGT absorb part of these errors for the conditions under which they were derived, but not errors that change with sun elevation, wind and time. These limitations concern the representation of the radiant exposure of a human body. The WBGT is nevertheless well established: ISO 7243 supports it for the screening of occupational heat stress, including work in the sun [19], and recent field studies of outdoor workers either use it as the reference for newer indices [28] or refine it for local climates [29]. This acceptance rests on tradition, simplicity and the existence of reference values, however, and not on a thermophysiological foundation. The WBGT contains no model of the human body; heat production, clothing and acclimatisation enter only through reference values and correction values, and as a linear-equation index [7] it does not describe the thermal state or

strain of a person. In practice the WBGT is, moreover, often not measured but estimated from standard meteorological data, with considerable differences between the methods [21,22]. Where the physiological strain of individual workers is the question, heat-strain risk indices tracked tympanic temperature and heart rate more closely than the WBGT in a study of 200 workers in steel and petrochemical plants [30]. The WBGT can therefore be used as an established screening tool for work and sport outdoors, within its reference values and with calibrated instruments, but it should not be read as a measure of the thermophysiological load of a person. Where the thermal load on a person has to be described, sun and shade have to be compared, or radiation and wind change quickly, it should be complemented by an energy-balance index with T_{mrt} determined for the human body [11].

5. Heat-Balance Indices: PMV and Equivalent Temperatures

5.1. Predicted Mean Vote (PMV)

The PMV [31] predicts the mean thermal sensation vote of a large group of people on a seven-point scale from −3 (cold) to +3 (hot), together with the Predicted Percentage of Dissatisfied (PPD). It is a thermal comfort index and not a thermal stress index. It was derived statistically from the thermal sensation votes of more than 1300 subjects in climate chambers and rests on a simplified steady-state heat balance of the body (Fanger's one-node model), not on the full energy balance with a thermoregulation model: skin temperature and sweat rate are calculated as comfort values that depend on activity alone [7]. It therefore belongs to the heat-balance indices only in this limited sense, and it is expressed as a vote and not as an equivalent temperature. It uses air temperature, T_{mrt}, air velocity, humidity, metabolic rate and clothing insulation. PMV/PPD is the basis of ISO 7730 [32] for indoor thermal comfort.

Advantages: includes all six classical variables; internationally standardised; well suited for buildings and vehicles. Limitations: a comfort index and not a heat stress index; developed for moderate indoor conditions near comfort, with validity limited to roughly −2 to +2; outdoors, with strong radiation, high wind, varying activity and adaptive clothing, it quickly leaves its range. The idea of the PMV, however, lives on in the Perceived Temperature (Section 5.5), which extends Fanger's approach to outdoor conditions.

5.2. Physiologically Equivalent Temperature (PET)

PET [33,34] is defined as the air temperature at which, in a typical indoor setting ($T_{mrt} = T_a$, air velocity 0.1 m s^{-1}, vapour pressure 12 hPa), the heat balance of the human body is maintained with the same core and skin temperatures as under the actual outdoor conditions. It is based on the two-node Munich Energy-balance Model for Individuals (MEMI). The standard person is a 35-year-old man, 1.75 m tall, weighing 75 kg, with light activity (80 W added to basic metabolism) and clothing of 0.9 clo. Thermal perception and stress classes for Western and Central Europe were given by Matzarakis et al. [35]; adapted classes exist for other climates, for example Taiwan [36].

PET is recommended in the German guideline VDI 3787 Part 2 [11] and is the most frequently used index in urban climate and planning studies. It can be computed with freely available tools such as RayMan and SkyHelios [37,38] and with the Python package biometeo [39]. In the urban climate model PALM-4U [40], the biometeorology module calculates PET, UTCI and PT together with a mean radiant temperature that accounts for buildings and vegetation [41], so that thermal indices become available for whole districts at high resolution, for example during a hot spell in Prague [42].

Advantages: the unit °C is intuitive for planners and the public; T_{mrt} and wind have a strong and realistic influence, so the effect of shade, trees and street design becomes directly visible; long experience and many comparable studies worldwide. Limitations: fixed clothing and activity; steady-state approach; the influence of humidity is comparatively weak; the classes are climate-dependent and must not be transferred without checking.

5.3. Modified Physiologically Equivalent Temperature (mPET)

mPET [43] keeps the reference concept of PET but replaces the two-node body with a multi-node thermoregulation model and a more detailed clothing model in which clothing adapts to air temperature. As a consequence, mPET responds more realistically to humidity and to changes in clothing, which makes it more suitable for warm and humid climates and for seasonal analyses. Open Python scripts for mPET, together with PET, UTCI, PMV and SET* and auxiliary functions for T_{mrt}, humidity and wind conversion, are available in the package biometeo [39].

Advantages: improved physiology and clothing while remaining comparable to PET; better sensitivity to humidity; open implementation. Limitations: the index value is calculated for specified constant conditions; fewer applications and fewer validated classes than PET; not yet included in guidelines.

5.4. Universal Thermal Climate Index (UTCI)

UTCI was developed by Commission 6 of the International Society of Biometeorology and the European COST Action 730 [44]. It is based on the multi-node thermoregulation model of Fiala et al. [45] coupled with an adaptive clothing model. UTCI is the air temperature of a reference environment with $T_{mrt} = T_a$, a wind speed of 0.5 m s^{-1} at 10 m height and a relative humidity of 50%, in which a person walking at 4 km h^{-1} shows the same dynamic physiological response as in the actual environment; at high air temperatures, the reference vapour pressure is limited to 20 hPa, that is, if the vapour pressure at 50% relative humidity exceeds 20 hPa, it is set to 20 hPa [46]. An assessment scale with ten categories from extreme cold stress to extreme heat stress is provided.

Advantages: state-of-the-art thermophysiology; valid over the full range of climates from −50 °C to +50 °C; one scale for heat and cold; good for weather services, climatology and international comparison [27]. Limitations: activity is fixed (walking), so resting people or workers are not represented; the operational version is a polynomial approximation valid only within defined input ranges; wind must be given at 10 m height, which is often overlooked in urban studies with pedestrian-level wind; the index is less intuitive for planners than PET because the reference person walks. Although the underlying Fiala model simulates the time course of the physiological response, the index itself is evaluated for given constant conditions and does not describe the exposure history of a moving person.

5.5. Perceived Temperature (PT)

The Perceived Temperature ("gefühlte Temperatur") is the core of the Klima-Michel model of the German Meteorological Service [47,48]. It extends Fanger's PMV approach to outdoor conditions: the reference person (Klima-Michel) walks at about 4 km h^{-1} and chooses clothing between summer and winter clothing so as to be as comfortable as possible; outside this comfort zone, the revised version uses Gagge's two-node model (PMV*) to obtain realistic skin and core temperatures and skin wettedness, which improves the description of sultry conditions [3,48]. PT is expressed as the air temperature of an isothermal reference environment ($T_{mrt} = T_a$) with only a slight draught and 50% relative humidity [3].

Advantages: long operational use in the DWD heat warning system and in climate assessments; adaptive clothing; one scale for heat and cold. Limitations: based on the PMV concept, which is empirical at its extremes; used mainly in Germany and some neighbouring countries, so international comparability is limited; the implementation details are less accessible to users than those of PET or UTCI.

5.6. Standard Effective Temperature (SET)*

SET* [49] is based on Gagge's two-node model [50]. It is the temperature of an isothermal reference environment with 50% relative humidity, still air and $T_{mrt} = T_a$, in which a person with standard clothing for the given activity would have the same skin temperature and skin wettedness as in the actual environment. SET* is used in ASHRAE Standard 55 [51], particularly to assess the cooling effect of elevated air speed indoors. For outdoor applications, Pickup and de Dear proposed OUT_SET* [52].

Advantages: physiologically well founded; includes activity and clothing; strong basis in building science. Limitations: developed mainly for indoor conditions; the treatment of outdoor short-wave radiation depends on how T_{mrt} is provided; the reference clothing changes with activity, which makes comparisons across activities difficult; outdoor assessment classes are less established.

6. Comparisons

Table 1 summarises the main characteristics of the nine indices and assigns each of them to its group (empirical, screening or heat balance). Three differences stand out. First, only the WBGT (through the globe) and the energy-balance indices take radiation into account; HI and DI describe shade conditions. Second, the indices assume different persons: PET a person with light activity, UTCI and PT a walking person, SET* and PMV an activity chosen by the user. Third, the reference environments differ, so equal numbers do not mean equal conditions. A PET of 35 °C and a UTCI of 35 °C describe different weather situations and belong to different assessment categories.

Table 1. Overview of the nine thermal indices discussed in this perspective (T_a: air temperature; RH: relative humidity; v: wind speed; T_{mrt}: mean radiant temperature; T_{nw}: natural wet-bulb temperature; T_g: globe temperature; M: metabolic rate; I_{cl}: clothing insulation).

Index	Origin/Reference	Inputs	Human Model	Main Field of Use	Main Strength	Main Limitation
HI empirical	[12,13]	T_a, RH	Implicit (walking adult, shade)	Public heat warnings (USA), epidemiology	Simple, well known	No radiation, no wind; heat only
DI empirical	[16]	T_a, RH	None	Climatology of warm/humid regions	Long time series possible	Empirical classes; no radiation, no wind
WBGT screening	[18,19]	T_{nw}, T_g, T_a	None (screening)	Occupational health, sports, military	Reference values for work and sport	Special instruments or estimation; globe not body-like; heat only
PMV comfort index; simplified heat balance	[31,32]	T_a, T_{mrt}, v, RH, M, I_{cl}	Simplified steady-state heat balance (one-node)	Indoor comfort, buildings, vehicles	All six classical variables	Valid only near comfort; not for outdoors
PET heat balance	[11,34]	T_a, T_{mrt}, v, RH	Two-node (MEMI), 80 W, 0.9 clo	Urban climate, planning, health, tourism	Intuitive °C; strong T_{mrt} and wind effect	Fixed clothing; weak humidity effect
mPET heat balance	[43]	T_a, T_{mrt}, v, RH	Multi-node, adaptive clothing	Urban climate, humid climates	Better humidity and clothing response	Fewer applications and classes
UTCI heat balance	[44,46]	T_a, T_{mrt}, v (10 m), RH	Fiala multi-node, adaptive clothing, walking 4 km h^{-1}	Weather services, climatology, health, international studies	Heat and cold, all climates	Fixed activity; 10 m wind; polynomial range
PT heat balance	[47,48]	T_a, T_{mrt}, v, RH	Klima-Michel (PMV-based + Gagge), walking	DWD warnings, climate assessment	Adaptive clothing; heat and cold	Mainly national use
SET* heat balance	[49,51]	T_a, T_{mrt}, v, RH, M, I_{cl}	Two-node (Gagge)	Indoor and semi-outdoor comfort, air movement	Physiologically founded, activity variable	Outdoor classes less established

7. Which Index for Which Purpose?

The choice of an index should start with three simple questions: What decision will be based on the index? Which person and activity are relevant? Which data are available, in particular on radiation? Table 2 translates typical questions into recommendations. It is not a ranking of indices; it reflects the principle that the purpose determines the tool.

Table 2. Simple decision path from the practical question to a suitable index.

Practical question	Recommended index	Remarks
Public heat and cold warnings	UTCI or PT for heat and cold; PET where established; HI for heat warnings only, where it is the national standard	Keep the index the public knows; link thresholds to health data.
Heat stress at work, sports, mass events	WBGT (ISO 7243) [19]; detailed models (e.g., PHS, ISO 7933 [24]) above reference values	Consider metabolic rate, clothing and acclimatisation; add an energy-balance index under strong sun.
Indoor comfort in buildings and vehicles	PMV/PPD (ISO 7730) [32], SET* [49] for elevated air speed	Adaptive comfort models for naturally ventilated buildings.
Urban planning, trees, shading, street design	PET or mPET; UTCI as alternative	Needs spatially resolved T_{mrt} and wind at body height (1.1 m) for PET and mPET and at 10 m for UTCI (e.g., RayMan, SkyHelios, SOLWEIG, ENVI-met, PALM-4U, biometeo).
Climatology, tourism climate, climate change scenarios	PET or UTCI	Use frequency classes; state the assessment scale used.
Epidemiology with station data only	HI or air temperature as simple exposure; UTCI/PET when T_{mrt} can be estimated	Report the algorithm; test sensitivity with more than one index.
Humid tropical and subtropical climates	mPET, UTCI; PET with regional classes	Check validity of classes for the local population.

The software named in Table 2 is documented in the literature: RayMan [37], SkyHelios [38], SOLWEIG [53], ENVI-met [54], the urban climate model PALM-4U with its biometeorology module [40,41] and the Python package biometeo [39].

Choosing among PET, mPET and UTCI. For urban planning and outdoor thermal comfort assessment, three indices compete, and Table 3 compares them with respect to the criteria that matter for the choice. All three need the same four meteorological inputs (air temperature, humidity, wind and T_{mrt}), so the data requirements differ less than the assumptions behind them. PET and mPET expect wind at body height (1.1 m) and UTCI at 10 m, which makes UTCI easier to apply to standard weather-station and reanalysis data and PET and mPET easier to combine with microscale models of street canyons. PET assumes a fixed person (80 W, 0.9 clo) in a steady-state two-node

model, mPET lets clothing adapt to air temperature and responds more realistically to humidity, and UTCI is derived from a multi-node model for a walking person with adaptive clothing. As a rule of thumb, PET is the first choice where established guidelines and classes exist, as in VDI 3787 Part 2 [11], and where the effect of design measures such as shade and trees has to be shown to planners; mPET is preferable in warm and humid climates and for seasonal analyses; UTCI is preferable where results must be comparable across regions or linked to warnings, and for large-scale analyses [6]. Comparative field studies show that the answer is not universal: on a campus in Xi'an, UTCI agreed with the votes of the users at all four sites, whereas PET and SET* needed local correction at some of them [4], and in a park in Kathmandu comfortable values of 30.0 °C PET and 28.5 °C UTCI were found [5]. Each value must be read on its own scale: 30.0 °C PET lies well above the 18–23 °C range of "no thermal stress" in the Central European PET scale, and 28.5 °C UTCI lies above the 9–26 °C range of "no thermal stress" in the UTCI scale. Whatever index is chosen, the assessment classes should be checked against local thermal perception.

Table 3. Criteria for choosing among PET, mPET and UTCI.

Criterion	PET	mPET	UTCI
Human model	Two-node model (MEMI), steady state	Multi-node model with adaptive clothing	Fiala multi-node model with adaptive clothing
Person	Standard person, 80 W, 0.9 clo (fixed)	Standard person; clothing adapts to air temperature	Walking at 4 km h^{-1}; clothing adapts
Wind input	1.1 m (body height)	1.1 m (body height)	10 m
Humidity	Weak influence	More realistic response	Reference vapour pressure limited to 20 hPa
Assessment scale	Climate-dependent classes; regional adaptation needed	Few validated classes	Ten fixed categories, cold to heat stress
Typical use	Urban planning, health, tourism, guidelines (VDI 3787-2 [11])	Warm and humid climates, seasonal analyses	Warnings, climatology, health, international comparison
Software	RayMan, SkyHelios, biometeo, PALM-4U	biometeo	biometeo, pythermalcomfort, PALM-4U

8. Discussion

Why are there so many thermal indices? One reason is the complexity of the subject itself: the thermal state of a human being depends on many interacting factors—meteorological, physiological, behavioural and even cultural—and every index is a simplification that keeps some factors and drops others. Another reason is the wish of users for simplicity. A weather service needs one number that can be broadcast; an occupational physician needs a threshold; a planner needs a map. Each of these users has, over time, adopted or developed the index that serves their purpose. The variety of indices is therefore largely a consequence of different purposes.

Problems arise when indices are used outside their purpose. Four errors are frequent in the literature and in practice. First, indices are compared as if equal numbers meant equal conditions, although reference persons and reference environments differ. Second, the mean radiant temperature is treated as a minor input: it is estimated from air temperature, measured with an unsuitable instrument, or modelled without stating the method. Because T_{mrt} is, in sunny and calm conditions, the dominant input of the energy-balance indices outdoors, errors in T_{mrt} can be the largest single source of error in such situations; under overcast, windy or nocturnal conditions, air temperature, wind and humidity weigh more [8]. ISO 7726 requires an accuracy of ±5 K for T_{mrt} [55]. Calibrated globe thermometers can give useful estimates of T_{mrt} under defined conditions, for example in shade, at night or in sheltered places, and they remain the sensor of the WBGT. In sunshine, however, their errors are often larger and depend on sun elevation, wind, globe size and urban form [25]: in an evaluation against integral radiation measurements in Hong Kong, globe-based methods underestimated T_{mrt} for most of the day, with the largest errors at low sun and at sunlit sites [56], whereas a comparison with a body-shaped cylinder at eight urban locations found that a globe overestimated T_{mrt} in sun-exposed places with a high sky view factor [26]. Globe values should therefore be treated as approximations whose uncertainty is reported; for pedestrians in sunshine, integral radiation measurements, or models validated against them, are the better reference. Third, wind input is taken from the wrong height, for example pedestrian-level wind for UTCI, which expects wind at 10 m, or 10 m wind for PET, which expects wind at the height of the body's centre of gravity, that is, 1.1 m above ground [3,11]. Fourth, assessment classes are transferred from one climate to another without testing them against the thermal perception of the local population. A review of 31 calibration studies from hot-humid regions found, for example, that the lower threshold of the neutral range of (m)PET needs to be lowered, whereas those of SET* and UTCI need to be raised [7].

Each of the indices has its place. The simple indices remain valuable where data are limited, where long historical series are needed, or where the public is used to them. It would be neither realistic nor helpful to replace

the Heat Index in American warnings or the WBGT in occupational health overnight. However, whenever sun, shade, wind and surfaces make a difference—in the street, on a square, in a park, at a beach or on a construction site—an index based on the human energy balance is required, and the quality of the result depends strongly on the quality of T_{mrt}. The equivalent temperatures PET, mPET, UTCI, PT and SET* are, despite their differences, much closer to each other than to the simple indices, because they all take the heat exchange of the body into account.

Three recommendations follow for users. (1) Choose the index according to the decision to be made and the relevant person and activity, rather than out of habit. (2) Report transparently: index and version, software, input heights, method for T_{mrt}, and assessment scale. Open implementations such as RayMan, SkyHelios, biometeo, pythermalcomfort and the PALM-4U biometeorology module make results reproducible [37–41,57]. (3) Where decisions carry high stakes, use more than one index and present the range; agreement between indices increases confidence, disagreement shows where assumptions matter.

Finally, the heat-balance indices discussed here (PMV, PET, mPET, UTCI, PT and SET*) describe a standard person under specified environmental conditions, for which an index value is calculated; the simple indices (HI, DI and WBGT) contain no model of the human body. This is not the same as the underlying physiological model: PMV, PET and SET* are based on steady-state heat balances, whereas the multi-node thermoregulation models behind mPET and UTCI can simulate transient responses. Even then, the published index value refers to given constant conditions and a standard person, not to the exposure history of a real person. This is why transient (non-steady-state) approaches are needed. Outdoors, radiation, wind and activity change within minutes, and the body reacts with a delay, so that the thermal state of a person depends on what happened before. The thermoregulation models behind UTCI and mPET can describe such changes, but the indices themselves are not fully integrated with them: the UTCI is a polynomial approximation of the response to given constant conditions, and mPET is likewise evaluated for specified constant conditions. Even multi-node models have limits for very rapid changes [7]. Real people move between sun and shade and between indoors and outdoors, and they differ in age, health and acclimatisation. Older people, children, outdoor workers and people with pre-existing illness are the groups most at risk, yet they are rarely represented by the reference persons. Future developments—transient approaches that follow the exposure history, individualised reference persons and realistic clothing—will bring the indices closer to the human being. Until then, the best practice is to understand the tool one uses.

9. Conclusions

Thermal indices are tools made for a purpose. The Heat Index and the Discomfort Index describe heat in the shade from temperature and humidity, the WBGT is an established screening index for work and sport, though not founded on thermophysiology, and the PMV is a thermal comfort index for indoor conditions, not a heat stress index. PET, mPET, UTCI, PT and SET*, in contrast, are equivalent temperatures based on the human energy balance; because they take radiation and wind into account, they are generally the better choice for outdoor questions in planning, climatology and warning systems.

Equal numbers do not mean equal conditions, since reference persons, reference environments and assessment scales differ between the indices. Outdoors in sunshine, the mean radiant temperature is a key input, and its measurement or modelling, including the uncertainty of globe-based estimates, must be documented as carefully as the choice of the index itself. In the end, the choice should follow the decision to be supported, the human being concerned and the data available—simple where possible, detailed where necessary.

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Use of AI and AI-Assisted Technologies

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