Curiosities about Thermal Indices Estimation and Application

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To date, it is well known that the effect of heat or cold on human beings cannot be described and quantified based only on one single meteorological or thermo-physiological parameter [1]. Since the effects of thermal environments on humans have been quantified, more than 160 thermal indices have been designed according to human thermal physiology and sensation [1]. From the plethora of indices, mostly the thermo-physiological indices are suitable for the relevant quantification of the atmospheric environment. They can be applied for different human biometeorological issues for assessing the short-term impacts of weather and the long-term development of climate [1].

Only twelve out of 165 indices are classified to be principally suitable for human biometeorological evaluation of climates for urban and regional planning: this requires that the thermal indices provide an equivalent air temperature of an isothermal reference with minor wind velocity. Furthermore, thermal indices must be traceable to complete human energy budget models consisting of both a controlled passive system (heat transfer between body and environment) and a controlling active system, which provides a positive feedback on temperature deviations from neutral conditions of the body core and skin, as is the case in nature [2,3].

Accordingly, the following five indices can be described as appropriate: Universal Thermal Climate Index (UTCI) [4], Perceived Temperature (PT) [5], Physiologically Equivalent Temperature (PET) [6–8], modified Physiologically Equivalent Temperature (mPET) [9,10], and rational Standard Effective Temperature (SET*) [11,12]. Recent studies also show the relevance of thermal indices and their justification to thermal perception for different parts and regions of the world [13,14].

Thermal bioclimate or, in general, human thermal stress factors are linked to contingency planning, protection of health, occupational safety and health, regional and urban planning, design of open spaces, architecture of single buildings, management of indoor conditions, various aspects of tourism and recreation areas, and research associated with climate change. It contributes to heat warnings and medical issues in weather forecasting [1,15]. All these facts require a rational, thermo-physiologically consistent assessment of the human thermal environment [1]. This is frequently accomplished by applying thermal indices. There is a long and extended discussion in human biometeorology about such thermal indices and which of them is the best and the most appropriate [1,13]. This question has to be accompanied by the aim of the study and the application methodology. Therefore, this question cannot be answered comprehensively.

For heat issues and its respective quantification, most of the indices behave similarly and provide specific and relevant results, i.e., definition of thresholds of heat in combination with epidemiological studies, including heat-related mortality [16]. For moderate stress (cold or heat), a general thermal comfort range as a result of acclimatization and cultural and social factors is not possible for global range justification. The same is also specifically true for cold conditions for several areas in the world.

Most important is the fact that the recent thermal indices (PET, mPET, UTCI, etc.) are not a simple algebraic or statistical formula or model like the wind chill or Humidex. They rely on energy exchange between body surfaces and internal heat production by

Citation: Matzarakis, A. Curiosities about Thermal Indices Estimation and Application. *Atmosphere* **2021**, *12*, 721. <https://doi.org/10.3390/atmos12060721>

Received: 1 June 2021

Accepted: 2 June 2021

Published: 4 June 2021

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humans, and as mentioned before, the application of single energy fluxes or the results of the “energy balance” is difficult to understand. Therefore, the concept of the equivalent temperature is an approach, which is not only helpful, but a “gentle” solution that can moreover be shared more easily with non-experts as well.

Because of the complexity of the energy balance equation and the extracted thermal indices, they have to be calculated with specific numeric models or programs [17]. There are several calculation possibilities, mostly in meso- and microscale models, and many of them are freely available [17,18].

In general, it is common for all thermal indices to have the same input parameters, being: (1) Two thermo physiological factors, i.e., (i) metabolism or activity and (ii) clothing; and (2) Numerous meteorological factors, i.e., (i) air temperature, (ii) air humidity, (iii) wind speed, and (iv) mean radiant temperature.

For the incorporation of the thermo-physiological factors, usually there is consensus regarding the matter of clothing. Here the approach based on the heat resistance of clothing is used. The heat resistance of clothing is described in unit of clothing (clo) (e.g., 0.9 clo means a business suit for men) and based on tables the clothing factors can be assumed [19,20]. Rarely is the moisture transfer of clothing included because of the complexity and accessibility level required. In most of the cases, especially for the quantification of typical and hot conditions, the knowledge of heat transfer of clothing only in terms of clo units fulfils more than 90% of the requirements. The question in the calculation of thermal indices is concerning clothing, i.e., how does each index consider clothing? An automatic selection or default values are the most proposed possibilities (Table 1). PET and SET* have defined and fixed values for their calculations. mPET provides the option to calculate automatically or by selection of values. UTCI and PT use an approach which is adapted on typical clothing behavior, which in many cases cannot be applied globally.

Table 1. Clothing and heat production (metabolism/activity parameters) for thermal indices input.

Index	Clothing	Metabolism/Activity
PET	Default value	Activity
mPET	Default value or adjusted based on temperature	Activity, adjustable
PT	Adjusted based on temperature	Total Metabolism
SET*	Default value	Total Metabolism
UTCI	Adjusted based on temperature clothing behavior for middle European clothing	Total Metabolism

The implementation of the heat production of the human body is the second thermo-physiological parameter and depends on several other parameters like age, sex, height, and weight [19]. For calculation of thermal indices, the heat production can be estimated in different ways (Table 1). The production of heat is dependent on the metabolism, and this can be divided into basic and active metabolism. The unit for metabolism is watt (W), such as for all energy balance fluxes. This is in contrast to the energy balance of surfaces in W/m^2 because of respective division of the human body's surfaces. Depending on the requirements of the index, metabolism or activity have to be selected. PET requires activity, and PT metabolism and UTCI have default defined values. Therefore, caution in the calculation is important concerning this issue.

Additionally, the following points should be mentioned:

- (i) Several thermal indices from different models or procedures should be considered.
- (ii) different activities or increased human heat productions usually are not in line with the definition of a thermal index, e.g., PET is strictly defined for an activity of 80 W and therefore any desired effects might not be visible in the results as anticipated.

- (iii) to see differences, including for gender or age, only the energy fluxes can show sensitivities for the human body exposures and strains.

For the meteorological input parameters, some issues have to be mentioned and considered, which are in some cases easy to handle. As mentioned, the advantage of the proposed thermal indices is that all require the same input parameters, namely: air temperature (T_a), air humidity (relative humidity (%) or vapor pressure (hPa)), wind speed (m/s) and for the three-dimensional exchange of short- and long-wave radiation fluxes of the human body, the main radiant temperature (T_{mrt} ($^{\circ}\text{C}$)). All these parameters can more or less be obtained by being measured in-situ or modeled [21].

All the meteorological input data are required for the height of the gravity center of the human body, which is 1.1 m from the ground [1,19,20]. Table 2 indicates the different requirements, which have to be considered in the preparation of input data and thermal indices calculations. The only discrepancy is wind speed, where according to the definitions of UTCI, wind speed should be incorporated at a height of 10 m.

Table 2. Required measurement/input height for all meteorological input parameters and thermal indices.

Parameter/Index	T_a ($^{\circ}\text{C}$)	RH (%) / VP (hPa)	Wind (m/s)	T_{mrt} ($^{\circ}\text{C}$)
PET	1.1 m	1.1 m	1.1 m	1.1 m
mPET	1.1 m	1.1 m	1.1 m	1.1 m
PT	1.1 m	1.1 m	1.1 m	1.1 m
SET*	1.1 m	1.1 m	1.1 m	1.1 m
UTCI	1.1 m	1.1 m	10 m	1.1 m

The availability of data for air temperature is very high for a different reason. Many official measurement stations exist for weather forecasts but also for the recording of background climate. In addition, there are several possibilities of modelled data from global climate, regional climate, or microscale models. Reanalysis and seasonal forecast data also provide a good database. The question is about the appropriateness of measured and modelled data. Most of the people live in urban areas and the official stations are installed in a specific location as a result of the abovementioned reasons of weather forecast or climate assessment. Stations are mostly far away from the point or area of interest and the data cannot directly be used for appropriate estimations and calculations due to the spatial variability of air temperature within cities. Beside observational data, which finally has to be modified and adjusted in terms of the point of interest, modelled data should be utilized considering the spatial and temporal resolution of this data. For air temperature data, the representatives should be considered and pointed out, including when undertaking thermal indices calculations.

Air humidity data in human biometeorological studies are often expressed as relative humidity or vapor pressure. For calculations, only one parameter is required, depending on the calculation procedure. Accuracies, availability, and requirements are the same as for air temperature.

Wind speed is required at 1.1 m height and wind speed data are generally harder to obtain since accurate representation in temporal and spatial dimension is required. Existing wind speed measurements are mostly not in the appropriate height of the human gravity center and therefore they have to be adjusted to a 1.1 m height [20]. For this purpose, simple but also complex approaches can be applied depending on the air and the applicability of the study or analysis performed. In most of the cases, the official wind speed data are measured at 10 m height according to WMO guidelines. The most simple approaches are the logarithmic wind profile considering the roughness conditions of the surrounding [22], or by calculation of the wind speed based on meso- or microscale models [23–25]. In several cases, especially for microscale conditions and complex urban conditions, when

approaching wind direction in terms of the quantification and appropriate inclusion of wind speed, roughness should be known at a high spatial resolution [10]. It has to be mentioned that the effect of wind speed particularly in urban and microscales can vary significantly and can have a strong effect on the different thermal indices [17]. In addition, it has to be mentioned that wind speed is one of the parameters which can be modified with planning/design measures and is absolutely crucial for the development of adaptation strategies and possibilities for climate change issues.

The most interesting meteorological and extraordinary parameter for thermal indices calculation is the radiation balance or budget of the human body, which can be expressed as an input parameter. The human body can be approximated as a cylinder or sphere. There is no way to measure T_{mrt} directly, instead it needs to be approached via different influencing factors, these being short- and long-wave radiation fluxes within a three-dimensional setup [19,20,26]. Therefore, the short-wave radiation fluxes, such as global radiation (direct solar and scattered solar) and reflected surfaces, are required. In complex environments, multiple reflections of the solid surfaces should be known. For long-wave radiation, the atmospheric radiation of the atmosphere and the radiation of the solid surfaces are important. The knowledge of the parts of the upper and lower hemisphere of the human environment needs to be expressed in terms of the sky view factor and the effect of it on the different short- and long-wave radiation fluxes [17,19,20,26].

T_{mrt} is defined as “the uniform temperature of a surrounding surface giving off blackbody radiation (emission coefficient $\epsilon = 1$) which results in the same radiation energy gain of a human body as the prevailing radiation fluxes which are usually very varied under open space conditions.” Given the considerably lower radiation fluxes indoors, T_{mrt} usually corresponds to indoor air temperature, but in sunny outdoor locations it can be more than 30 K higher. T_{mrt} can either be calculated from the individual solar (short wave) and terrestrial (long wave) radiation fluxes, or it can be derived from integral in-situ measurements. The following radiation fluxes are significant: direct solar radiation, diffuse solar radiation, and reflex radiation (from the ground and other surrounding surfaces). Long-wave radiation is composed of thermal radiation in the atmosphere and thermal radiation from the ground and other surrounding surfaces [20]. Several approaches exist in order to estimate T_{mrt} . Many studies provide possibilities of how to solve this issue based on measurements and modeling. However, and in accordance with the existing literature, attention about the accuracy, representativeness, and the appropriateness of the data is perpetually paramount [20,26–28].

In light of such dynamics, when approaching thermal indices the transfer of wind and radiation data which are not measured at the point of interest becomes necessary [27,29]. The same is also valid for the application of microscale models where the validation of the results is required [30].

The issue of the distance of the site in relation to the data also exists in the models regarding the resolution of the raster data that are used.

Table 3 provides the variability of meteorological and thermo-physiological input parameters in the spatial and temporal dimension. It has to be pointed out that concerning the temporal variability, all meteorological parameters have a high temporal variability that is dependent on both seasonality and diurnal variability. Concerning the spatial variability, the highest is for wind speed and solar radiation, especially within the built environment. For thermo-physiological input factors, there is a strong adaptation possibility because of individual human behavior.

Table 3. Spatial and temporal variability of meteorological input parameters for thermal indices.

Parameter	Spatial	Temporal
Air temperature	Medium	High
Air humidity	Medium	High
Wind speed	Big	Medium
Mean radiant temperature	Big	High
Activity	None	High/medium
Clothing value	None	Medium

For the application of thermal indices, there is a demand concerning the temporal resolution of the meteorological data, which is expressed in Figure 1. Long-term analysis based on monthly mean values provide less accurate and appropriate results because of the daily variability of the inherent parameters. For mean daily data, there is less possibility of obtaining the maxima and minima conditions during the day and there is difficulty considering frequencies of thresholds, amongst other factors. For calculations based on minimum or maximum conditions in a day, it also becomes more complicated when attempting to approach the quantification of real conditions. Synoptically, hourly, or 10 min data fulfil most of the requirements concerning comprehensive climate analysis in terms of human biometeorological and epidemiological impact research.

Figure 1. Temporal resolution of data requirements for calculation of thermal indices.

In many cases for the estimations of thermal indices, micro- and mesoscale models are applied based on one-day simulations in order to provide information for planning approaches and the development of strategies and/or measures against climate change and guideline development. These kinds of simulations provide less appropriate temporal information and are limited in the relevance pertaining to the results in the spatial context. Therefore, they should be validated and correlated to the intrinsic limitations of the undertaken simulation.

Following this line of reasoning, it is urgently necessary not only to find/utilize the appropriate index, but also to clarify whether the model used meets the requirements and

addresses the specific target question. Furthermore, in addition to meeting such targets, the effectiveness of the communication technique should also always consider its audience, including when working with non-climatic experts.

Associated with the aforementioned point, the dominant purpose for the calculation of thermal indices lies within the necessity of the development of adaptation possibilities concerning climate change. More concretely, within the urgent need for planning issues in cities we must protect humans, and thus, such augmenting risk factors must be approached in such a manner to protect human life [15].

The wholesome aim of this editorial is to pay attention to this specific issue in order to avoid possible confusion in the calculation of thermal indices. It focuses only on the requirements of input parameters for the calculation of thermal indices. Additional factors about thermal comfort or issues pertaining to thermal stress regarding different adaptation approaches and factors are not a point of discussion in this paper.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

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