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Mid-afternoon Outdoor Biometeorological Conditions in a Hot-humid Climate of Minna in Nigeria, West Africa during the Year 2012

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Authors' contributions

This work was carried out in collaboration among all authors. Author CAN designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors IO and CAN managed the analyses of the study. Author VNO managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The human biometeorological conditions at mid-afternoon during 12 months of 2012 in the city of Minna North-Central Nigeria have been evaluated based on energy budget indices (UTCI and PET) using climate parameters -air temperature, relative humidity, wind speed and solar radiation) observed at 15:00LST as input into the Rayman model. Air temperature demonstrated strongest significant correlation coefficient (r) with UTCI and PET (r= 0.91, r= 0.93) (P<0.0001) while windspeed show weakest association with them(r=-0.10, r=-0.20) (P<0.03, P<0.001) respectively. March and August were characterized by peak and slightest monthly thermal stress conditions according to both indices. The correlation coefficient between both indices was significantly (P<0.0001) very strong (r=0.98) and more noticeable for equivalent temperatures in strong stress thresholds (UTCI>=32°C, PET>=35°C), which shows that both indices can be used indifferently in warm climates. However, during May to October, UTCI better expressed warm conditions than PET

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mainly due to the difference in the definition of reference environment for both indices; this study is relevant to the urban sightseeing industry as tourists would most likely opt for a period of lesser thermal discomfort.

Keywords: UTCI; PET; heat stress; thermal environment; human biometeorological; Minna.

1. INTRODUCTION

Thermal environment evaluation is a significant field in human biometeorology due to its relationship with comfort and discomfort. Optimum performance and health can be actualized when individuals acclimatize their heat budget to the thermal environment. The body's physiological response (strain) due to atmospheric heat exchange with the body (stress) encompasses the term "thermal environment" [1]. About 162 climatic indices have been developed in the past 100years for heat stress assessment [2]; selecting appropriate Indices is also challenging [3], such that even already established indices were reviewed especially for warm and humid regions [4,5]. For a heat stress assessment method to be suitable, it must consider all pathways for "heat exchange between the body and the environment" as well as heat generation inside the body [6]. Energy balance models such as Universal Thermal Climate Index (UTCI), Physiologically Equivalent Temperature (PET), Perceived Temperature (PT), Standard Effective Temperature (SET*) have become popular among thermal comfort researchers in recent time because these models also known as heat budget models considers both thermo-physiological and physiological parameters in their simulations [7]. These models take into account all mechanisms of heat exchange in the human body. A comprehensive literature review of 110 peer-reviewed articles during 2001-2017 identified only 4 (Universal Thermal Climate Index (UTCI) Physiologically Equivalent Temperature (PET), Standard Effective Temperature (SET*), Predicted Mean Vote (PMV)) out of the 165 human thermal indices developed to be widely in use for outdoor thermal perception studies [8]. However, this present study will only consider UTCI and PET.

The UTCI is developed with the concept of an equivalent temperature which involved the definition of a reference environment (50% relative humidity but vapour pressure not exceeding 20hpa with calm air and radiant temperature equaling air temperature). This is described as the equivalent ambient temperature (°C) for a given combination of air temperature, humidity or vapour pressure, radiation and wind that will produce the same physiologic response (strain) [9,10,11,12]. The effort of over 45 scientists from 23 countries led to the development of the new UTCI [1]; its application and validation in different climate regions around the world has made it very popular and widely accepted in human Biometeorological studies [13,14,15]. The UTCI comparison with previous thermal stress indices shows that the UTCI represents specific locations, weather, and climate. The UTCI can express even slight differences in the intensity of meteorological stimuli. Besides, like the human body, the UTCI is exceptionally delicate to changes in ambient stimuli: temperature, solar radiation, wind and humidity. UTCI portrays thermal conditions' temporal variability better than other indices [11,16].

PET also follows the concept of an equivalent temperature based on the Munich Energy Balance Model for Individuals (MEMI) [17] and a reference environment (Mean Radiant Temperature MRT = air temperature, 50% humidity, vapour pressure of 12hPa and windspeed of 0.1m/s). It is characterized as the air temperature at which, in a typical indoor setting [18] (without wind and solar radiation), the energy budget of the human body is at equilibrium with the exact core and skin temperature as under complex outdoor conditions to be evaluated [18,19,20]. PET studies at different scales have been conducted around the world [21,12,22].

Climate change is a valid motivation for intensification of biometeorological studies in the hot-humid region, Orosa et al. [23] identified the potential for heatstroke risk due to climate change outdoor thermal comfort thresholds in humid climates. Thermal environment assessment based on energy balance stress models is not very common in Africa when compared to other continents around the world [24,25,26] despite the alarming reports of high-temperature values in hot-humid climate region of the continent. In Nigeria, however, a few studies have been conducted. Njoku and Daramola [21] assessed human comfort conditions in a tropical zone (Southwestern Nigeria) at 09:00LST and 15:00LST. The study result shows that thermal comfort varies seasonally with an increased level of discomfort during the transition to wet months (TWS) and dry months (DM) while thermal comfort improved during the little dry season (LDS), the temperature was observed to be the highest contributor to thermal discomfort level. Balogun et al. [27] calculated the PET and UTCI of selected meteorological stations in Nigeria at 06:00LST and 15:00LST. The result depicted an increase in thermal discomfort level from March to May and improved comfort conditions during the wet periods, 06:00LST characterized by "no thermal stress". The northern part of the country recorded cooler comfort conditions than the southern region, and meteorological stations considered recorded differing thresholds of thermal stress level. Omonijo and Matzarakis [28], in their analysis of the climate and bioclimate of Ondo state Nigeria, suggested that atmospheric parameters be incorporated into the health management systems of the country for the attainment of the Millenuim Development Goals (SDGs) in the health sector because their research findings included marked spatial and seasonal variation of thermal comfort and different grades of physiologic stress over the humid forest zone and derived savannah zone of Ondo state.

The Sudan-savannah and Sahelian climate regions of Nigeria are characterized by high-temperature values all year round [27], which calls for more study of the thermal environment on the regional and local scale. Previous effort to quantify the outdoor atmospheric impact on Minna metropolis's human body was based on simple indices that are just combinations of meteorological parameters [29]. This present paper is one of a few efforts to assess the outdoor human biometeorological conditions during mid-afternoon in the city of Minna, North-central Nigeria, during the 12 months of the year 2012 using two heat budget biometeorological indices (UTCI and PET). Afternoon thermal comfort evaluation is becoming very popular due to human activities within that period [30,31]. Also, 15:00LST in Africa's hot-humid tropical region is characterized by thermal discomfort level [21,32]. The objectives of this paper are to;

1) Analyze meteorological conditions responsible for heat stress
2) Evaluate biometeorological indices (UTCI and PET)
3) Examine the relationship between biometeorological indices and meteorological parameters
4) Examine the relationship between UTCI and PET

2. METHODOLOGY

2.1 Study Area

Minna is a capital city in the North-Central Nigeria state of Niger; it has a tropical savanna climate (Köppen-Geiger classification: Aw) with a pronounced dry period. Average temperature and sunshine duration per year are 27°C and 2672 hours, March and September are the warmest and coldest months with corresponding average temperature values of 30.2°C and 24.9°C while total annual rainfall averages 1209.7mm (http://www.climatemps.com).

2.2 Data

Daily meteorological data (air temperature, relative humidity, wind speed, solar radiation) observed at 15:00Local Standard Time (LST) (mid-afternoon) for the 12 months in 2012 from an Automatic Weather Station (AWS) sited at longitude 6.18°E, and latitude 9.62°N in Minna was utilized for this study. The AWS is part of a network of about 14 stations established in Nigeria for the Tropospheric Data Acquisition Network (TROJAN) project by the Centre for Atmospheric Research (CAR), which is an arm of the National Space Research and Development Agency (NASRDA). Owing to the dataset's irregularity, the authors decided to choose the most consistent period (2012) to evaluate the data archive.

2.3 UTCI and PET Simulation

UTCI is expressed mathematically as follows:

$$\text{UTCI}(Ta, MRT, v, RH) = Ta + \text{Offset}(Ta, MRT, v, RH) \quad \text{Eq. 1}$$

Where Ta =Air Temperature, MRT = Mean Radiant Temperature, v = Windspeed, RH = Relative Humidity. The offset which is the deviation of UTCI from the referenced air temperature depends on the actual observed values of the meteorological parameters (Ta, MRT, v, RH).

The Munich Energy Balance Model for Individuals (MEMI) (Eq. 2) which is meant for evaluating the thermal environment is the foundation for PET calculation and it is given as follows:

$$M + W + R + C + E_{sk} + E_{res} + E_{sw} + S = 0 \quad \text{Eq. 2.}$$

Where M = Metabolic heat production, W = mechanical Workload, R= Radiation net of the body, C = Sensible heat flux, E_{sk} = Latent heat due to diffusion through the skin, E_{res} = Latent heat due to respiration, E_{sw} = Latent heat due to sweating, S = Storage of heat. The energy loss or gain by the thermal environment is compared to the reference environment of the PET index (MRT = air temperature, 50% humidity, vapour pressure of 12hPa and windspeed of 0.1m/s), the air temperature of the reference environment is then adjusted until it is causing the same thermal load (stress) as the actual outdoor thermal environment, this equivalent temperature is the calculated PET.

Several free models have been developed over the year to simply calculate heat budget indices, they include Bioklima 2.6 (https://www.igipz.pan.pl/bioklima.html) and Rayman model (https://www.urbanclimate.net/rayman/description.htm). The Rayman Pro model version 2.1 [33,34] calculated UTCI and PET in this current work, the model requires meteorological parameters (air temperature, relative humidity, wind speed and solar radiation) and non-meteorological parameters (Metabolic rate and heat resistance of clothing) as input [35], The metabolic rate was set at their default values 135W/m^2 and 80W for UTCI and PET, respectively, while both indices assumed 0.9clo for heat resistance clothing in the calculation [36]. Details of how to use the model can be seen at https://www.urbanclimate.net/rayman/RayManManual.pdf. The output of the model calculation which is the equivalent temperature (UTCI and PET values) were then graded into their different thermal stress categories (Table 1); UTCI has ten classes of thermal stress level while PET has nine classes of thermal stress level [16,37,31,20,38].

3. RESULTS

3.1 Meteorological Conditions

Meteorological parameters collectively impact human comfort level; every variable that is part of heat balance models plays its role, evaluating them for the study period. The highest and lowest temperature at 15:00LST were observed on March 21st(40.5°C) and July 14th(20.5°C), while maximum and minimum relative humidity were recorded on September 1st(90%) and March 21st(6.7%), respectively. Windspeed highest and lowest values were observed on April 4th (3.55m/s) and June 27th(0.19m/s), whereas global solar radiation attained maximum and minimum values on July 10th and 14th, respectively.

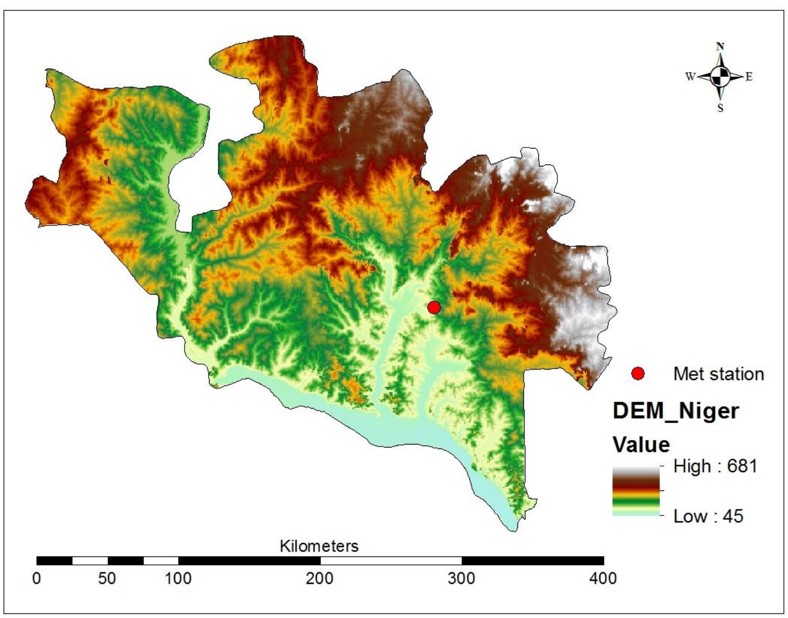

Fig. 1. Digital elevation model of the study area

Table 1. UTCI and PET categories of thermal sensation

Stress category	UTCI (°C)	PET (°C)
Extreme heat stress	>+46	>41
Extreme heat stress	+38 to +46	
Strong heat stress	+32 to +38	35 – 41
Moderate heat stress	+26 to +32	29 – 35
Slight heat stress		23 – 29
No thermal stress	+9 to +26	18 – 23
Slight cold stress	0 to +9	13 – 18
Moderate cold stress	-13 to 0	8 – 13
Strong cold stress	-27 to -13	4 – 8
Very strong cold stress	-40 to -27	
Extreme cold stress	<-40	<4

The mean and Standard Deviation (SD) of climate variables is depicted in the Table 2. The maximum and minimum monthly air temperature values were observed in March (37.6°C ±1.3) and August (26.8°C ±2.0) respectively, relative humidity highest and lowest mean values were recorded in August (69.9% ±8.7), and March (14.6% ±7.7) whereas windspeed maximum and minimum mean values were recorded in May (1.9m/s ±0.7) and November (1.4m/s ±0.5), solar radiation mean highest and lowest values were recorded in March (646.0W/m^2 ±113.3) and August (414.4W/m^2 ±216.9).

3.2 Biometeorological Conditions

Maximum and minimum values of UTCI (43.5°C and 19.2°C) and PET (50.2°C and 15.5°C) were recorded on March 21stand July 14th. Different thresholds of thermal perception were recorded during the 12 months studied. The study location was characterized by four classes of UTCI physiologic stress level ranging from "no thermal stress" to "very strong thermal stress," whereas six classes of PET physiologic stress level ranging from "slight cold stress" to "extreme heat stress" was recorded. UTCI thresholds were 2% "no thermal stress", 7% "moderate heat stress", 51% "strong heat stress" and 40% "very strong heat stress" level while PET observed 1% "slight cold stress", 1% "no thermal stress", 3% "slight heat stress", 15% "moderate heat stress", 38% "strong heat stress" and 42% "extreme heat stress" level. Table 3 show the number of days with strong heat stress thresholds according to both indices (e.g. UTCI>=32°C, PET>=35°C) were 338 days (92%) and 293 days (80%) respectively for the period examined.

The monthly mean and SD of the equivalent temperatures of both indices are depicted in Table 4. The maximum UTCI (41.2°C ±1.1) and PET (46.5°C ±1.6) was recorded in March while the minimum UTCI (32°C ±3.5) and PET (31.9°C ±5.5) was observed in August.

3.3 Relationship between Biometeorological Indices and Meteorological Parameters

Heat budget indices relationship with meteorological parameters (air temperature, relative humidity, wind speed and solar radiation) is depicted in Figs. 2 and 3. Save for windspeed (UTCI P<0.03 and PET P<0.001), the other parameters correlated strongly with indices at 99% (P<0.0001) significant level. UTCI and PET strongly correlated positively with air temperature (r=0.91 and r=0.93) and solar radiation (r=0.62 and r=0.63) respectively. However, both indices negatively correlated with relative humidity (r=-0.70 and r=-0.78) and wind speed (r=-0.10 and r=-0.20), respectively. The coefficient of determinant (R^2) and slope of the relationship between UTCI and meteorological parameters such as air temperature, relative humidity, wind speed and solar radiation were 0.84 and 0.90, 0.50 and -4.10, 0.01 and -0.02, 0.40 and 27.95, respectively, while PET coefficient of determinant (R^2) and slope of association with parameters in similar order were 0.87 and 0.61, 0.61 and -2.93, 0.03 and -0.03, 0.40 and 18.02.

Table 2. Mean and standard deviation of meteorological parameters for the months of 2012

Parameters		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temp.	Mean	33.7	35.8	37.6	34.5	31.5	29.7	27.7	26.8	28.4	30.8	34.7	34.7
	SD	2	1.2	1.3	1.7	2.2	1.7	1.8	2	2.5	1.3	1.4	1.1
R. Humidity	Mean	17.2	24.5	14.6	40.1	51.3	58.9	65.4	69.9	65.3	57.8	32.7	18.7
	SD	6.2	7.5	7.7	6.4	7.6	6.6	6.4	8.7	9.3	5	11.3	7.4
Windspeed	Mean	1.5	1.6	1.8	1.8	1.9	1.8	1.8	1.7	1.6	1.6	1.4	1.7
	SD	0.7	0.6	0.7	0.6	0.7	0.6	0.6	0.7	0.7	0.6	0.5	0.5
S. Radiation	Mean	522	555.9	646	556.9	535.4	486.2	472.1	414.4	444.5	491	497.7	486
	SD	53.3	89.1	113.3	175.2	165.7	189.2	208.4	216.9	212	156.5	96.5	81.3

Table 3. Days with strong heat stress at 15:00LST in different months

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UTCI>=32°C	30	29	31	29	30	28	24	20	26	30	30	31
PET>=35°C	29	29	31	29	26	24	11	9	17	27	30	31

Table 4. The mean and standard deviation of simulated biometeorological indices for the months of 2012

Indices		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
UTCI	Mean	37.0	40.2	41.2	39.5	36.8	35.0	33.1	32.0	33.7	36.4	38.8	37.7
	SD	2.7	1.3	1.1	2.3	2.5	2.5	3.2	3.5	3.8	1.8	1.5	1.4
PET	Mean	41.3	44.8	46.5	42.8	39.0	36.1	33.5	31.9	34.3	38.0	42.2	41.7
	SD	3.6	2.0	1.6	3.5	3.8	3.8	4.6	5.5	5.6	2.8	2.4	1.9

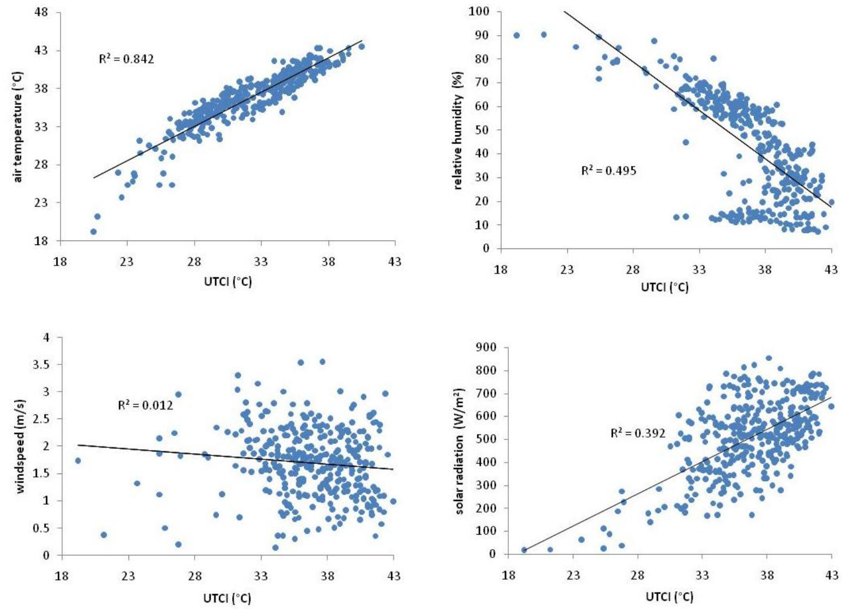

Fig. 2. Scatterplot and regression lines of UTCI and meteorological parameters

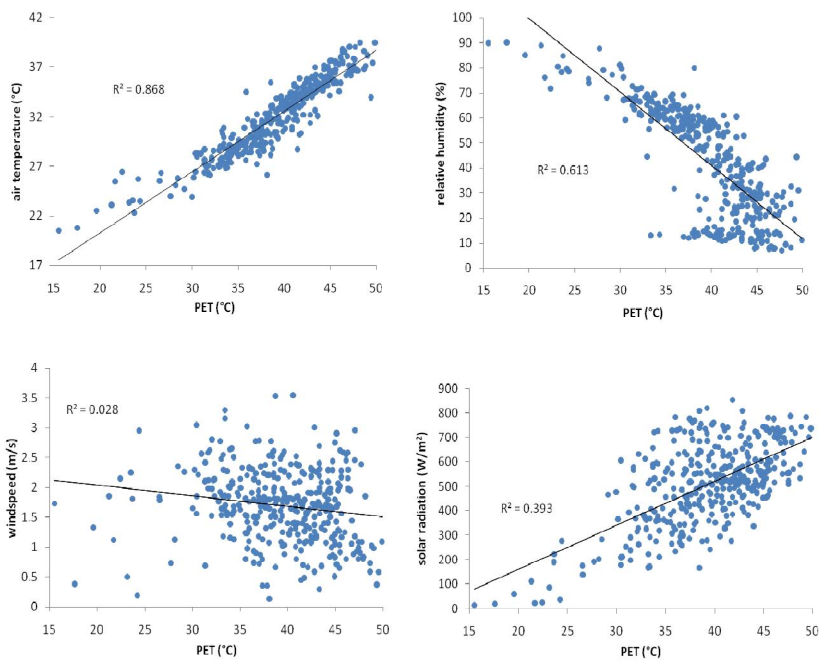

Fig. 3. Scatterplot and regression lines of PET and meteorological parameters

3.4 Correlation between UTCI and PET

Fig. 4 show the scatterplot of UTCI and PET. The correlation coefficient (r) for the period examined for both indices is 0.98; this strong relationship is significant (P<0.0001). For equivalent temperatures of strong heat stress (e.g. UTCI>=32°C and PET>=35°C), it can be seen that data points become more compact, which shows better association in warm conditions than in thermal neutrality and cold conditions.

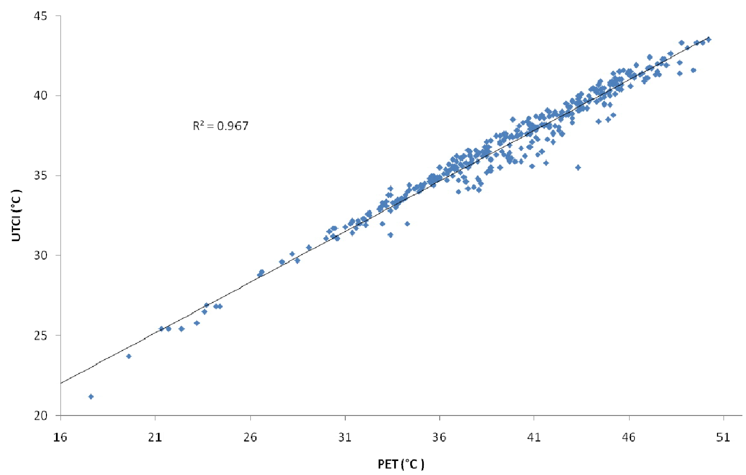

Fig. 4. Scatterplot of UTCI and PET

4. DISCUSSION

This study compared UTCI and PET in a hot-humid climate of Minna Niger state in North-Central Nigeria at 15:00LST daily for all months in 2012. March and August recorded mean highest and lowest air temperature values because March typifies the dry season's peak with prevailing sunny and cloudless conditions [39]. August is characterized by a cloudy atmosphere and cooler soil conditions, according to Adefisan et al. [40]. The air temperature was observed to have the most substantial influence on thermal stress conditions; this agrees with the findings of Balogun et al. [27]; Akinbobola et al. [25] (hot-humid climate), Vatani et al. [41] (arid climate); Blazejczyk et al. [11] (temperate climate). Relative humidity inversely associated with both indices, similar to Zare et al. [16] (arid climate). However, the decrease in the number of days with strong thermal stress conditions expected during the rainy months (April to October) when relative humidity and vapour pressure is high is only noticeable in PET; this disparity is mainly a result of the slight difference in the definition of reference environment for simulating both indices (UTCI: relative humidity 50% but vapour pressure =< 20hPa, PET: relative humidity 50% but vapour pressure =12 hPa), this study observed that during May to October when relative humidity and vapour pressure are high due to high moisture content in the study area UTCI yielded a higher number of days with strong heat stress category than PET (Table 3), this also agree with the findings of Matzarakis et al. [12] (temperate climate). The relationship between both indices and wind speed is negative and similar to the findings of Balogun et al. [27] in the hot-humid climate of Nigeria, although contrary findings were reported in an arid climate [16] and temperate climate [11]. Global solar radiation correlated positively with both indices.

In terms of physiologic stress categories, it is challenging to directly compare the thresholds' frequency in both indices because of the difference in the upper and lower limits of their thresholds' equivalent temperature values. For instance, in Table 1, the “no thermal stress” category for UTCI ranges from 9°C to 26°C (17°C) while PET ranges from 18°C to 23°C (5°C). However, the correlation between both indices in the scatterplot (Fig. 4) for high values of their equivalent temperatures shows their agreement in warm thresholds and suitability for hot-humid conditions even though UTCI exhibit an advantage over PET in the hot-humid climate of Minna during the wet period.

5. CONCLUSION

The result of this study will be a priceless asset to tourists visiting the study location; health policy makers can better understand the effect of a warming climate on human well being and productivity. Acknowledging the limitations of this study such as; (a) only 15:00LST in 24hours of the day was examined, (b) the monthly assessment was for 2012 alone, authors will, in conclusion, suggest further studies for other activity hours of the days and seasonal evaluation using higher temporal resolution data.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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